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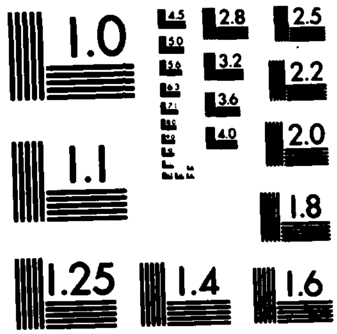


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NWC TP 4834, Part 5

AD-A146 173

# Evolution of the NWC Thermal Standard

## Part 5. Summary: Thermal Standard Development and Applications


by
Dr. Richard D. Ulrich
*Brigham Young University*


**JULY 1984**

**NAVAL WEAPONS CENTER**
**CHINA LAKE, CALIFORNIA 93555**







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# Naval Weapons Center

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## FOREWORD

This report is the fifth in a series of reports on the theory, design and development, and application of a device designated the "NWC thermal standard." The work described in this report was conducted from 1969 through 1982. The program was sponsored by the Naval Weapons Center and was accomplished by Brigham Young University under Contracts N60530-81-C-0039, N60530-80-C-0330, N60530-76-C-0091, N00123-76-C-1932, and N60530-77-C-0147. This program was supported by the Naval Air Systems Command under the Missile Propulsion Technology Block Program (AirTask A32-324A/008B/3F31-300-000). Mr. Lee N. Gilbert is the NWC technology manager for this program.

The technical coordinator for this project, Mr. H. C. Schafer, has reviewed this report for technical accuracy. This report is released for information at the working level and does not necessarily represent the views of the Naval Weapons Center.

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31 July 1984

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from p.3

(U) Part 1 of this report series described the theoretical concepts of a thermal standard. Part 2 presented a comparison of predicted and experimental data. Part 3 described use of the thermal standard to determine field thermal response of ordnance stored unsheltered. Part 4 presented the results of several years of data collection in the field, using the thermal standard, along with graphs and analysis of the data.

~~(U)~~ This part of the report series, Part 5, contains a summary of the work done with the thermal standard temperature-measuring device. Development of the device is described, and its applications are discussed. Future uses are suggested.

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\41
\42
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\45
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\47
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CONTENTS

# INTRODUCTION

This report is the fifth in a series of reports covering the development and application of a temperature-measuring device, designated the NWC thermal standard, which can be used to evaluate the thermal response of ordnance. Part 1 of this report series described the theoretical concepts of a thermal standard. Part 2 presented a comparison of predicted and experimental data. Part 3 covered the results of using the thermal standard in the field to determine the thermal response of ordnance (stored unsheltered) and described the cumulative probability 1473 versus temperature method of data presentation. Part 4 presented field data collected by using the NWC thermal standard. Thermal standards were located in various geographic areas; the temperature was monitored for a year or more at each location; the data were collected, analyzed, and reduced, and cumulative probability versus temperature curves were prepared. In addition, the data were integrated into the entire body of thermal data to produce a more usable world-wide cumulative probability versus temperature curve.[1]

The purpose of this part of the report series is to summarize the work done with the thermal standard temperature-measuring device. The development of the device and its application are described. In addition, future thermal standard uses are suggested.

The thermal standard was designed so that its reponse to thermal forcing functions could be correlated with any given ordnance item. These data have been used to predict the thermal response of ordnance up to 18 inches in diameter. The primary advantage is the elimination of a major portion of the work presently required to measure the response of an ordnance item stored at many locations over a many-year period to establish its "unique" thermal response during field storage and use.

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[1] Naval Weapons Center. *Evolution of the NWC Thermal Standard. Part 1. Concept; Part 2. Comparison of Theory With Experiment; Part 3. Application and Evaluation of the Thermal Standard in the Field; Part 4. Field Data for Temperate, Arctic, and Hot (Desert and Tropic) Zones*, by Richard D. Ulrich and Howard C. Schafer. China Lake, Calif., NWC, various dates. (NWC TP 4834, Parts 1-4, publications UNCLASSIFIED.)

# BACKGROUND

During recent years, military ordnance has been stored in many locations of the world. Frequently, time to collect weather data was not adequate to permit the estimation of storage temperatures for the specific locations. Because future locations for materiel storage cannot always be leisurely analyzed, it was thought necessary to develop some device which would represent all (or, at least, many) military items. This device was to be instrumented such that its thermal response to the environment could be monitored by relatively simple recording equipment. It should be such that its response could be predicted from weather bureau information. It should be massive enough to represent large, heavy objects; small enough to represent small objects; peaceful looking so no one would feel threatened by its presence (i.e., nonmilitary looking), and chemically stable so that its surface heat transfer properties could be maintained for several years in many climate types.

Those who have made thermal environmental studies in the past have sectioned the earth into many different thermal categories. However, for the purposes of storing military items and understanding their thermal response to the elements, three general categories or zones were deemed to be sufficient: temperate, arctic, and hot. In each zone, factors other than air temperature vary geographically (such as prevailing wind, humidity and precipitation, and elevation relative to sea level, nearby mountains or oceans, and so forth). These factors also blend, or fair, the three zones together. The proposed device was not intended to study the meteorological aspects of the earth but to observe the thermal response of an object to all of the weather factors combined. This makes the device an integrator rather than a differentiator.

The name given to the device was "NWC thermal standard." A plan was developed to make a number of these thermal standards and to expose them to many environments. The thermal response to the environments was to be monitored, and the data were to be handled statistically. That is, the thermal standard was to be exposed for many months, usually a few years, in one location; the thermal data were then to be statistically reduced to a form whereby cumulative probability of occurrence could be estimated. (This form eventually was determined to be cumulative probability versus temperature curves.) No particular effort was made to obtain data for a specific "design day." However, specific effort was made to locate the NWC thermal standards in the "hottest" and "coldest" locations of the world. Most hot, cold, and temperate areas were chosen with the idea of obtaining a world-wide data base of thermal environments so that a designer of future hardware could combine a specific temperature estimate with his knowledge of probability of failure (or performance decline) as a function of temperature and could then make appropriate engineering decisions.

The thermal standard has proven to be a valuable tool for (1) predicting hourly surface temperatures of adjacent ordnance, replacing the need to instrument a large variety of ordnance; (2) predicting cumulative probability versus temperature curves for various items; and (3) generating a "typical day" and, using only 10% of the daily maximum and minimum temperatures, predicting the annual cumulative probability versus temperature curve accurately for various ordnance items.

## DESCRIPTION OF THE NWC THERMAL STANDARD

The development, validation, and applications of the NWC thermal standard have been described previously.[1] This work is summarized below for the convenience of the reader.

### THERMAL FORCING FUNCTIONS

When ordnance is to be stored for relatively long periods of time (many days, months, or years), it is necessary to predict future temperatures it may encounter (its "temperature future"). Any object will respond to the elements making up its environment. The elements which influence the temperature of a body are called "thermal forcing functions."

The thermal standard was devised to collect data on the effects of thermal forcing functions that exist at particular locations. (The thermal standard was designed so that its response to the thermal forcing functions could be correlated with any given ordnance item. These data, when used to predict the response of similar ordnance, would eliminate a major portion of the work presently needed to measure the response of many different ordnance items stored at a given location.)

The term "thermal forcing functions" is defined as those parameters external to an object which effect heat transfer to the object and thus affect the temperature of that object when it is placed in the observation space. Some of these forcing functions are:

1. Direct radiation from the sun
2. Reflected solar radiation from the atmosphere
3. Reflected solar radiation from the ground
4. Convected heat to and from the ambient air
5. Heat transfer resulting from surface phase change
6. Heat transfer resulting from precipitation

7. Any heat-generating devices, such as heater blankets, or chemical reactions
8. Conduction to adjacent solid objects
9. Convection to ground water
10. Direct radiation from the ground
11. Long wavelength radiation heat exchange with the atmosphere

These factors are generally functions of time, direction, latitude, clouds, ground color, nearby structures, humidity in the air, etc. They are also functions of nearby water bodies and mountains and other geographic features. The time variable includes both time of day and time of year for long-term storage. However, for a single ordnance item, diurnal variations will be a much more significant time variable, with seasonal variables considered as "steady state changes"; that is, the changes are slow compared to the time constant of the ordnance.

The luxury of actually measuring each of the thermal forcing functions separately is appealing from the standpoint of heat transfer analysis. If each external boundary condition were known for a given location and if the internal structure for heat conduction (or internal heat radiation or convection) were given, the problem would be reduced to one which could be solved directly.

Any relatively large sized object made from a composite of materials and placed in the environment has a complicated temperature distribution as well as a "hard-to-predict" maximum temperature, temperature gradients, and thermal stresses. It is usually impossible to specify the boundary conditions, let alone calculate the internal temperature distribution. Generally, the procedure for determining the thermal forcing functions would be to place "instruments" near the object and measure various quantities, such as air temperature, radiant flux, wind velocity, etc. However, mainly because of the wide variety of local functions, the instrument package would be large, hard to specify, and probably incomplete.

An alternate approach is to place a "typical" object in the space and observe its response to all of the thermal forcing functions. This "typical" object integrates all the forcing functions, rather than differentiating among them. This changes the emphasis of analysis from "What are the forcing functions?" to "What is the response to the forcing functions?" This approach leads to the concept herein called a "thermal standard" (the typical object being the thermal standard).

The thermal standard concept was to build a device having a thermal response that would provide sufficient information to allow one to predict the thermal response of a wide variety of materiel that might be placed in or near the same "space" at a later date. The term "thermal response," as used here, consists of temperature-time variation at a few discrete points on and within the body.

In summary, the thermal standard must be sensitive to the thermal forcing functions but need not necessarily differentiate the mode of heat transfer, and it should respond in about the same manner as a large variety of ordnance. The thermal standard should provide sufficient data to allow determination of its thermal response. This could then be applied as boundary conditions for actual ordnance, and thermal responses could be predicted.

The thermal standard might be likened to a "spy in the enemy's camp" when it comes to predicting ordnance temperature, compared to predictions using weather station data, which "surround the camp."

## SPECIFICATIONS

### Shape

Generally, the ordnance to be simulated will be bombs, rockets, or objects of similar shape. These shapes may be approximated by combinations of planes, cylinders, and spheres. The most likely shape is cylindrical. However, the use of a cylinder as a standard would necessitate having a standard orientation of the axis, like east-west or north-south. Since the problem of heat transfer coefficent estimation for cylinders, based on data on spheres of comparable size, is straightforward; since radiation is essentially independent of geometry; and since spheres do not have an orientation problem, a spherical shape was used for the thermal standard. The implication is that, if the thermal response for a sphere in a given environment is known, then the response of a cylinder to the same thermal forcing functions could be estimated with sufficient accuracy for ordnance design purposes. Also, the spherical shape does not have a "military" appearance, which simplifies its location at peaceful U. S. and foreign sites.

### Size

The determination of size of the thermal standard was based primarily on the size range of objects to be simulated. Assuming the major items to be missiles, bombs, and large projectiles, a characteristic size range of interest to the Navy would thus be 2.5 to 24 inches, with each diameter about equally likely; the logical size would then be the geometric mean of 6.5 inches in diameter. However, both of these premises are in error. Little information is available concerning the likelihood of size distribution for future weapons. The choice of size for a thermal standard was based on the consideration that it be larger than a single lumped size but be small enough that it would not be effectively infinite in size, since it should yield information suitable for design in as large a size range as possible. Combining these with other size considerations, a 6-inch diameter was chosen to satisfy all criteria.

## Materials

The choice of materials used in the thermal standard was based on the following considerations. In general, the ordnance to be simulated may be represented by a relatively thin metal (steel or aluminum) shell surrounding a volume of propellant, explosive, air, or electronics. The inside material usually has a low thermal conductivity and may be separated from the shell by a thermal insulation material.

Three material properties were considered for simulation by the thermal standard: the thermal diffusivity of the explosive or propellant, the thickness of the metal shell, and the absorptivity of the outside surface to solar radiant energy. A brief survey indicated that the thermal diffusivity of many explosives and propellants (even when metal-particle laden) did not vary over a wide range. Also, the values of those surveyed were about the same as the values for many organic materials, such as rubber. In addition, the analysis indicated that the final result (i.e., maximum surface temperature) was not sensitive to the exact value of thermal diffusivity, so long as it was low. This led to other considerations for the particular choice of internal material, such as handling, shaping, and change in dimension with temperature. Based on these properties, a typical room-temperature-vulcanizing (RTV) rubber was used.

The metal shell has little effect on the heat transfer analysis. The thermal resistance for radial heat flow is negligible for any metal of reasonable thickness (less than 0.25 inch). The metal shell could have the effect of making the boundary conditions, as seen by the rubber mass, the same in all directions. However, since it is desired to maintain the thermal standard in the field for several years, and often in chemically corrosive or mechanically erosive atmospheres, the choice of metals was based on considerations other than a heat transfer analysis. A noncorrosive stainless steel (SS304L) was used for the shell. Its stability over several years in many environments has been demonstrated.

## THERMAL STANDARD DESIGN

Several thermal standards were built for preliminary testing and evaluation. The standards were 6-inch-diameter spheres, had thin stainless steel shells with an absorptivity to solar radiation of about 0.6, and were filled with room-temperature curing rubber (RTV 511, with thermal properties as follows: thermal conductivity, K, = 0.18 Btu/hr-ft-°F; density, $\rho$, = 73.5 lb/ft; and specific heat, $c_p$, = 0.48 Btu/lb-°F). They were instrumented with five thermocouples placed as follows (see also Figure 1):

| Thermocouple number | Location |
|---|---|
| 1 | Top |
| 2 | 68 degrees counterclockwise from top |
| 3 | 20 degrees clockwise from bottom |
| 4 | 68 degrees clockwise from top |
| 5 | Center of sphere |

Thermocouples 1 through 4 were welded to the stainless steel skin.

## FIELD LOCATIONS OF THERMAL STANDARDS

A number of thermal standards were located and monitored, as shown below.

| Location | Years monitored |
|---|---|
| China Lake, Calif. (2) | 1968-1978 |
| Death Valley, Calif. | 1970-1978 |
| Panama Canal | 1968-1976 |
| Subic Bay, Philippine Islands | 1966-1974 |
| Queensland, Australia (2) | 1971-1972 |
| Thailand | 1971-1972 |
| Alert Canadian Forces Base (Northern Canada; near North Pole) | 1972-1973 |
| Resolute Bay, Canada (island) | 1972-1973 |
| Fort Greely, Alaska (inland) | 1969-1975 |
| Fort Richardson, Alaska (coast) | 1969-1975 |
| Provo, Utah (Brigham Young University) | 1977-1982 |
| Tooele, Utah (Tooele Army Depot) | 1980-1982 |
| Fort Belvoir, Va. (Engineering Topological Laboratory) | 1978-1982 |
| Atlanta, Ga. (Georgia Institute of Technology) | 1978-1980 |
| Lafayette, Ind. (Purdue University) | 1978-1980 |
| Seal Beach, Calif. (Naval Weapons Station) | 1980-1982 |

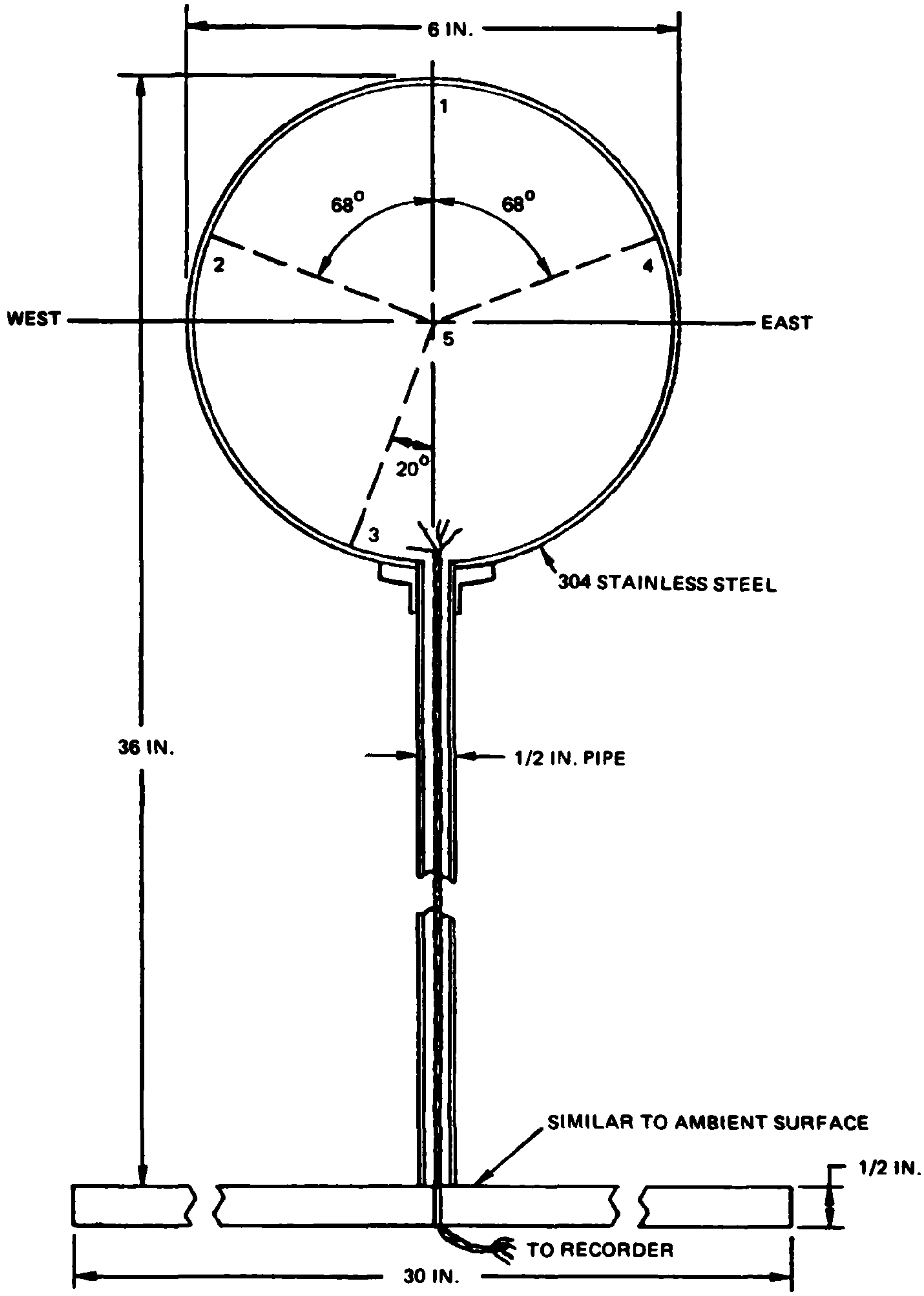


FIGURE 1. Thermal Standard Cross Section.

These locations were chosen both because they represent general areas typical of temperate hot arid, hot humid, cold arid, or cold humid zones and because each had personnel available to oversee the data collection and service the instrument.

A typical field installation of the NWC thermal standard was shown in Ref. 1 (Part 2, page 5).

## DATA ANALYSIS THEORY AND TECHNIQUES

### STATISTICAL CUMULATIVE PROBABILITY STUDIES

A series of statistical comparisons was made using the 1974 hourly temperatures from the top thermocouple of the China Lake 36-inch-high thermal standard as a baseline. The objective was to determine the minimum amount of data that would produce cumulative probability versus temperature (CP-T) curves which would compare favorably with the CP-T curves for all hours (8760 hours) of the year. First, different fractions of hourly data were chosen, and CP-T curves were drawn and compared with the baseline. Second, daily data were chosen (in which all the temperatures for any given day were used, but not all days were used) and compared. Table 1 shows the results of the various comparisons, including the <u>maximum</u> differences between the baseline and the graph.

For example, "Every third day" means that all 24 hourly temperatures for every third day are used in generating the cumulative curve, beginning with 3 January 1974. The results show that using data in hourly groups rather than in daily groups produces less error. The results also show that the amount of data can be selectively reduced by 90% without producing an error greater than 3%.

It was postulated that, for most days, the thermal standard has essentially the same general temperature-time pattern and that the only variation from day to day is the spread of maximum and minumum temperature values. Hence, approximations of the CP-T curve were attempted using only the daily maximum and minimum. The accuracy of this method was unsatisfactory. A better approximation using the sine function was attained by changing the ratio of points generated above the mean temperature to points generated below the mean from 6 points above and 6 points below to 5 points above and 8 points below. This ratio of 5/8, or 0.625, was close to the ratio of the actual data (0.628). The maximum error on the CP-T curve of this approximation was 3.1%.

However, a better approximation to the baseline curve was formed by computing the average ratio of a specific hour of a "typical day" by

TABLE 1. Comparison of Selected Amounts of Data.

| Data graphed | Amount of data used, % | Maximum error, % |
|---|---|---|
| Every other hour | 50 | 0.25 |
| Every third hour | 33 | 0.85 |
| Every fifth hour | 20 | 0.85 |
| Every fifth hour, randomly selected | 20 | 1.1 |
| Every seventh hour | 14 | 1.0 |
| Every tenth hour | 10 | 1.0 |
| Every tenth hour, randomly selected | 10 | 3.8 |
| Every 15th hour, randomly selected | 7 | 4.2 |
| Every 20th hour | 5 | 1.7 |
| Every 20th hour, randomly selected | 5 | 3.1 |
| Every 30th hour | 3 | 2.8 |
| Every 50th hour | 2 | 4.2 |
| 100 random points, plus year maximum and minimum | 1 | 5.0 |
| Every other day | 50 | 0.25 |
| Every third day | 33 | 0.85 |
| Every fourth day | 25 | 0.85 |
| Every fifth day | 20 | 1.4 |
| Every fifth day, randomly selected | 20 | 2.0 |
| Every ninth day | 12 | 3.6 |
| Every tenth day | 10 | 1.7 |
| Every tenth day, randomly selected | 10 | 1.9 |
| Every 20th day | 5 | 3.6 |
| Every 20th day, randomly selected | 5 | 4.7 |
| Every 40th day | 2 | 5.6 |

subtracting the minimum temperature for the day from the hourly temperature and dividing by the difference between the maximum and minimum temperatures. These hourly ratios were computed in two different ways. In the first case, the ratios for each day were calculated, and then the ratio was averaged over the entire year to find the typical temperature curve. The curve thus generated did not, however, include a maximum of one and a minimum of zero. In the second case, the temperatures for each separate hour of the day for all the days were first averaged over the year, and then these averages were used to calculate the ratios for the typical temperature curve. This method did provide a maximum of one and a minimum of zero.

The second method generated the most accurate CP-T curves of the two. The maximum error was less than 2.2%. This method was called the typical day (TD) method. Table 2 gives the values of the TD ratios for any time of day for the various locations used. The equation used was:

$$(\text{TD ratio})_i = \frac{(\Sigma T)_i - (\Sigma T)_{min}}{(\Sigma T)_{max} - (\Sigma T)_{min}}$$

where

i is the $i^{th}$ hour

$\Sigma$ is the sum over the $i^{th}$ hour for 365 days

$(\Sigma T)_{min}$ and $(\Sigma T)_{max}$ are the minimum and maximum $i^{th}$ hour sums

The successful prediction of ordnance CP-T curves by the use of TD ratios means that the diurnal temperature ratios are different but similarly shaped. Of course, clouds, rain, and other factors are present during the year, but these effects were averaged out by this method of data handling. Since all the days are "similar," only a representative sample of days is necessary to generate the CP-T curve for the year. The comparisons made were designed to show that limitations exist for each set of TD ratios.

It was determined that the TD ratios from the NWC thermal standard top thermocouple could be used to accurately predict the top skin CP-T curves of various ordnance items. However, those TD ratios did not predict as well a motor inside a container; therefore, the TD ratios for thermal standard center thermocouples were developed and successfully used for internal thermocouple locations. These also are shown in Table 2.

TABLE 2. Typical Day Ratios, Top and Center Thermocouples.

a. Temperate Zone.

| Hour | Fort Belvoir | | Georgia Tech[a] | Brigham Young Univ. | |
|---|---|---|---|---|---|
| | Top | Center | Top | Top | Center |
| 00 | 0.1068 | 0.1792 | 0.138 | 0.1928 | 0.2272 |
| 01 | 0.0750 | 0.1357 | 0.1179 | 0.1679 | 0.2325 |
| 02 | 0.0570 | 0.0977 | 0.1122 | 0.1337 | 0.1846 |
| 03 | 0.0394 | 0.0738 | 0.067 | 0.1162 | 0.1573 |
| 04 | 0.0197 | 0.0434 | 0.0069 | 0.0991 | 0.1363 |
| 05 | 0.0041 | 0.0226 | 0.0000 | 0.0818 | 0.1128 |
| 06 | 0.0000 | 0.0026 | 0.00401 | 0.0705 | 0.0918 |
| 07 | 0.0574 | 0.0000 | 0.06525 | 0.0000 | 0.0000 |
| 08 | 0.2223 | 0.0593 | 0.30223 | 0.0141 | 0.0027 |
| 09 | 0.4525 | 0.2116 | 0.5243 | 0.1826 | 0.0953 |
| 10 | 0.6827 | 0.4117 | 0.7344 | 0.3810 | 0.2527 |
| 11 | 0.8527 | 0.6139 | 0.9147 | 0.6069 | 0.4553 |
| 12 | 0.9499 | 0.7705 | 0.9690 | 0.7858 | 0.6370 |
| 13 | 0.9879 | 0.8831 | 0.9937 | 0.9338 | 0.8061 |
| 14 | 1.0000 | 0.9522 | 1.0000 | 1.0000 | 0.9306 |
| 15 | 0.9651 | 0.9940 | 0.901 | 0.995 | 0.9902 |
| 16 | 0.8870 | 1.0000 | 0.771 | 0.9537 | 1.0000 |
| 17 | 0.7646 | 0.9590 | 0.6113 | 0.8821 | 0.9902 |
| 18 | 0.6215 | 0.8673 | 0.4894 | 0.7746 | 0.9347 |
| 19 | 0.4753 | 0.7321 | 0.3698 | 0.6402 | 0.8263 |
| 20 | 0.3623 | 0.5870 | 0.2931 | 0.4991 | 0.7053 |
| 21 | 0.2996 | 0.4548 | 0.3817 | 0.3817 | 0.5559 |
| 22 | 0.2012 | 0.3434 | 0.1963 | 0.2977 | 0.4368 |
| 23 | 0.1566 | 0.2641 | 0.166 | 0.2367 | 0.3472 |

[a]Center thermocouple for Georgia Institute of Technology is the same as the center thermocouple for Fort Belvoir.

b. Arctic Zone (From Fort Greely, Alaska).

| Hour | Top | Center | Hour | Top | Center |
|---|---|---|---|---|---|
| 01 | 0.021 | 0.060 | 13 | 0.979 | 0.975 |
| 02 | 0.000 | 0.029 | 14 | 0.934 | 0.995 |
| 03 | 0.005 | 0.008 | 15 | 0.856 | 1.000 |
| 04 | 0.018 | 0.004 | 16 | 0.856 | 0.950 |
| 05 | 0.095 | 0.000 | 17 | 0.773 | 0.871 |
| 06 | 0.215 | 0.040 | 18 | 0.668 | 0.768 |
| 07 | 0.342 | 0.112 | 19 | 0.555 | 0.647 |
| 08 | 0.516 | 0.205 | 20 | 0.413 | 0.504 |
| 09 | 0.703 | 0.332 | 21 | 0.296 | 0.397 |

TABLE 2. (Contd.)

b. Arctic Zone (Contd.)

| Hour | Top | Center | Hour | Top | Center |
|---|---|---|---|---|---|
| 10 | 0.852 | 0.495 | 22 | 0.213 | 0.284 |
| 11 | 0.955 | 0.698 | 23 | 0.141 | 0.204 |
| 12 | 1.000 | 0.877 | 24 | 0.078 | 0.127 |

c. Hot Zones.

| Hour | Top thermocouples | | | | | Center thermocouples | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Subic Bay | Panama | Australia | China Lake | Jungle[b] | Subic Bay | Panama | China Lake | Jungle[c] |
| 01 | 0.039 | 0.049 | 0.040 | 0.1433 | 0.043 | 0.085 | 0.098 | 0.2264 | 0.092 |
| 02 | 0.026 | 0.035 | 0.023 | 0.1170 | 0.028 | 0.060 | 0.070 | 0.1842 | 0.065 |
| 03 | 0.018 | 0.028 | 0.015 | 0.0879 | 0.020 | 0.041 | 0.051 | 0.1434 | 0.046 |
| 04 | 0.008 | 0.017 | 0.005 | 0.0657 | 0.010 | 0.024 | 0.035 | 0.1060 | 0.029 |
| 05 | 0.000 | 0.008 | 0.000 | 0.0378 | 0.000 | 0.010 | 0.020 | 0.0683 | 0.015 |
| 06 | 0.029 | 0.000 | 0.025 | 0.0144 | 0.010 | 0.000 | 0.010 | 0.0303 | 0.000 |
| 07 | 0.098 | 0.002 | 0.160 | 0.0000 | 0.086 | 0.027 | 0.000 | 0.0000 | 0.014 |
| 08 | 0.260 | 0.072 | 0.340 | 0.0693 | 0.224 | 0.109 | 0.013 | 0.0007 | 0.061 |
| 09 | 0.482 | 0.288 | 0.580 | 0.2561 | 0.450 | 0.250 | 0.125 | 0.0978 | 0.188 |
| 10 | 0.697 | 0.534 | 0.815 | 0.4871 | 0.682 | 0.434 | 0.325 | 0.2731 | 0.380 |
| 11 | 0.854 | 0.752 | 0.930 | 0.7019 | 0.845 | 0.622 | 0.550 | 0.4760 | 0.586 |
| 12 | 0.947 | 0.910 | 0.990 | 0.8625 | 0.949 | 0.782 | 0.745 | 0.6523 | 0.764 |
| 13 | 1.000 | 1.000 | 1.000 | 0.9560 | 1.000 | 0.909 | 0.899 | 0.7959 | 0.904 |
| 14 | 0.973 | 0.972 | 0.890 | 1.0000 | 0.945 | 0.988 | 0.980 | 0.9007 | 0.984 |
| 15 | 0.904 | 0.902 | 0.758 | 0.9920 | 0.855 | 1.000 | 1.000 | 0.9677 | 1.000 |
| 16 | 0.778 | 0.776 | 0.635 | 0.9382 | 0.730 | 0.978 | 0.960 | 0.9999 | 0.969 |
| 17 | 0.613 | 0.638 | 0.475 | 0.8481 | 0.575 | 0.924 | 0.880 | 1.0000 | 0.902 |
| 18 | 0.446 | 0.514 | 0.295 | 0.7158 | 0.418 | 0.818 | 0.770 | 0.9578 | 0.794 |
| 19 | 0.288 | 0.347 | 0.205 | 0.5715 | 0.280 | 0.657 | 0.634 | 0.8662 | 0.646 |
| 20 | 0.200 | 0.238 | 0.150 | 0.4205 | 0.196 | 0.477 | 0.482 | 0.7283 | 0.480 |
| 21 | 0.142 | 0.168 | 0.110 | 0.3096 | 0.140 | 0.335 | 0.352 | 0.5690 | 0.344 |
| 22 | 0.103 | 0.124 | 0.085 | 0.2488 | 0.104 | 0.235 | 0.254 | 0.4411 | 0.245 |
| 23 | 0.073 | 0.095 | 0.065 | 0.2058 | 0.078 | 0.165 | 0.188 | 0.3507 | 0.177 |
| 24 | 0.050 | 0.073 | 0.050 | 0.1733 | 0.058 | 0.114 | 0.142 | 0.2863 | 0.125 |

[b] Average of Subic Bay, Panama, and Australia.

[c] Average of Subic Bay and Panama.

## APPLICATION OF TYPICAL DAY METHOD

Cumulative distribution curves for the thermal standard temperatures generated used the TD ratios and maximum and minimum temperature data for every tenth, 20th, and 40th day and also for random tenth, 20th, and 40th days. The error using every tenth day (for example) was less than 3.5%; the error for the 20th and 40th days was unacceptably high.

Based on the success of the typical day method using only 10% of the daily maximum and minimum temperatures, it was decided to examine a variety of ordnance items whose thermal responses could be predicted in this manner. Table 3 shows which ordnance items were used and the TD ratio source used in generating the prediction curves. (The baseline data had been taken earlier for other purposes, but are shown here as if the data had been taken afterward.) The actual curves were presented in Ref. 1 (Part 3 of this report series) and are not repeated here.

As a matter of interest, an attempt was made to predict the CP-T curve for the ambient air; surprising success was achieved. Following this line of reasoning, it was suspected that the TD ratios developed from the center thermocouple would better predict the CP-T curve for *any internal* thermocouple. This proved to be so. Even the ambient air temperature was better predicted this way. As an internal extreme, the CP-T curve for a magazette was tried and again was surprisingly successful. This gave reason to believe that CP-T curves for other internal storage locations could also be accurately predicted by the center thermocouple.

An attempt was made to use the China Lake thermal standard top thermocouple to predict the CP-T curve for a container in Australia. This was so unsuccessful that it was necessary to generate the TD ratios from the top thermocouple in the Australian thermal standard. These were used to predict some Australian dump stored ordnance CP-T curves; however, the results were not as good as those for China Lake. Actually, there was some question as to the validity of the baseline for all the Australian CP-T curves. Thus, no negative conclusions concerning the CP-T predictions may be drawn because of these poor comparisons.

The results in general indicate that the thermal standard, using the TD ratios, is an excellent means for predicting yearly CP-T curves using only *72 data points* taken from a yearly record. The cost of producing CP-T curves is thus reduced by a factor of more than 100.

Based on this success using the TD ratios appropriate to the location of the thermocouple on the object and to the geographic location of the stored item, more than 2500 CP-T curves were generated. Not only did this provide CP-T curves at a cost of about $3.50 each (compared to $350-500 each if hourly data were to be used), but also much data were reduced that otherwise might not have been.

TABLE 3. Typical Day 10% Maximum-Minimum Comparisons.

| Ordnance item/location | TD ratio used: area/thermocouple | Maximum error, % |
|---|---|---|
| All-up Sparrow motor/top skin | China Lake/top | 2 |
| Sparrow container/top | China Lake/top | 3.5 |
| 20-mm ammunition/inside top round | China Lake/top | 3 |
| Sparrow motor in container/top skin | China Lake/top | 4.5 |
| Ambient air/Stevenson shelter | China Lake/top | 4 |
| Ambient air/Stevenson shelter | China Lake/center | 3 |
| 20-mm ammunition/middle row center | China Lake/center | 2 |
| 20-mm ammunition/top row center | China Lake/center | 1.5 |
| Zuni motor in container/top, east | China Lake/center | 3.5 |
| Sparrow motor in container/skin | China Lake/center | 2.5 |
| Thermal standard/center | China Lake/center | 2 |
| Sparrow container/center | China Lake/center | 8 |
| Magazette/air | China Lake/center | 2.5 |
| Thermal standard/top | Australia/top | 2 |
| 7.62 NATO ammunition/top row | Australia/top | 2 |
| 2.75 rocket out of container/top | Australia/top | 3 |
| Sparrow in container/top | Australia/top | 7 |
| Sparrow motor/top | Australia/top | 6 |
| ASROC motor/top | Australia/top | 6 |

## COMPARISON OF CUMULATIVE AND NORMAL DISTRIBUTIONS

### China Lake Data

The cumulative distribution curves for the China Lake thermal standard top and center thermocouples were compared to a normal distribution having the same mean ($\mu$) and standard deviation ($\sigma$). The objective of the comparison was to see if the curves were close enough to the normal to justify use of normal distribution confidence intervals to predict the maximum error caused by using only part of the data to draw the baseline curve. The curves are shown in Figures 2 and 3. In

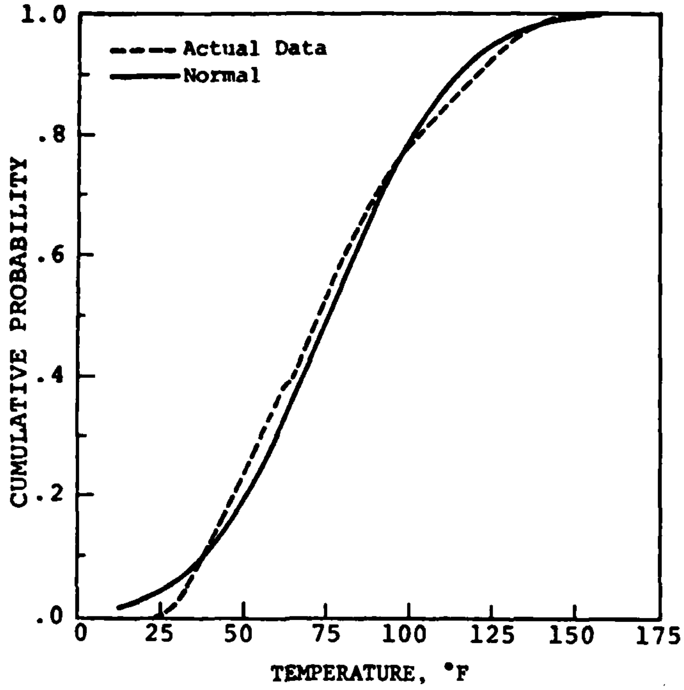


FIGURE 2. Normal Curve and Baseline, Thermal Standard, Top--China Lake.

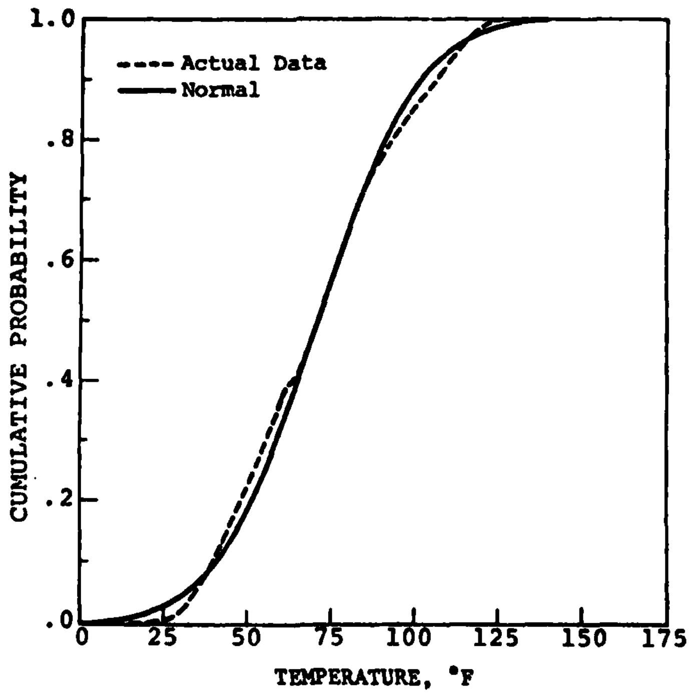


FIGURE 3. Normal Curve and Baseline, Thermal Standard, Center--China Lake.

both cases, the graphs show the data to be close to a normal distribution except at the extremes, where the actual data are not as severe. This appears to be true in all real-to-normal comparisons. The longer tails of the normal distribution are more clearly seen in the observed frequency profiles (Figures 4 and 5). The greater severity of the normal curve indicates that the normal confidence intervals would be conservative estimates for the actual data; i.e., the actual data bandwidths of error are smaller than those of the normal curve.

The hypothesis that this is true was tested by graphing 50 randomly selected samples of 5% of the total data (438 points per sample) and comparing the maximum error between the samples and the baseline to a normal confidence interval. All 50 of the samples were no more than 6.7% away from the baseline. This corresponds to the bandwidth expected for a 96% confidence interval. The probability that all 50 samples would lie within a 9% confidence interval if normally distributed is approximately 13%. This value is low enough to justify the conclusion that the temperature data are probably more conservatively distributed than the normal distribution. At any rate, it is safe to use normal confidence intervals to predict the bandwidths of error caused by data reduction.

## Australian Data

A comparison of the normal and Australian thermal standard top thermocouple is shown in Figure 6. The data deviate more from the normal than do the China Lake data, the most significant deviation being at the top extreme, where the actual data are more severe than the normal. A better profile of the data is given in Figure 7, which shows that the data resemble a Chi Square distribution, with a high peak and a long tail to the right side of the mean. The greater severity in the tail means that the bandwidth of error might be *greater* than the normal; however, this could be offset by the compactness of the data in the center region, as revealed in the high peak. To check this hypothesis, a comparison similar to the one described for the China Lake data was made. The bandwidth was a maximum 6.7% away from the baseline. This corresponds to an 85% confidence interval. (The interval is smaller than in the China Lake case because only 304 points per sample were used.) The probability that all 50 samples would be inside an 85% interval, if normally distributed, is only 0.006. This is at the 0.01 level of significance (highly significant). It can be concluded that the normal confidence intervals provide conservative estimates for the Australian data also.

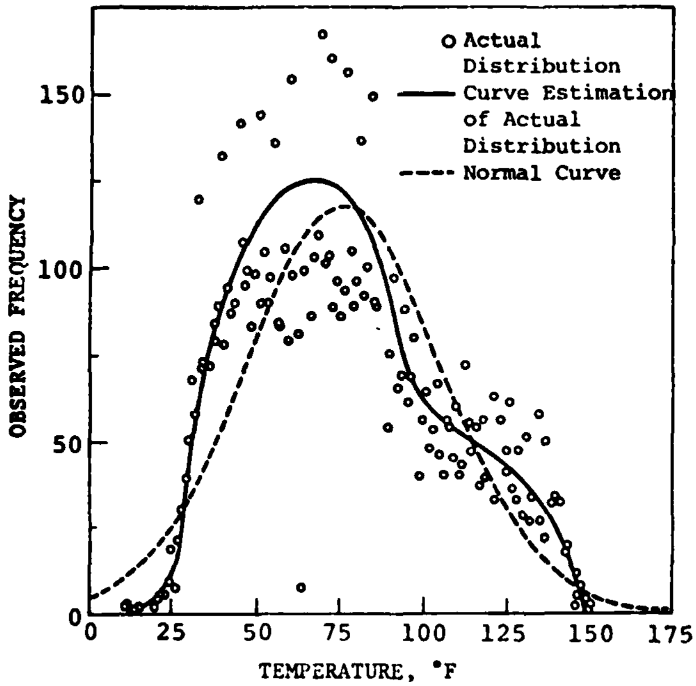


FIGURE 4. Observed Frequency Profile of Normal and Thermal Standard, Top--China Lake.

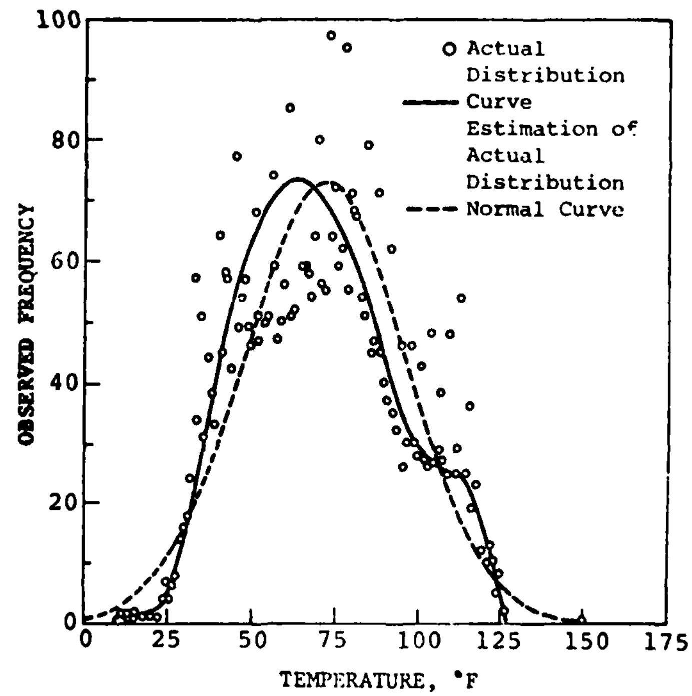


FIGURE 5. Observed Frequency Profile of Normal and Thermal Standard, Center--China Lake.

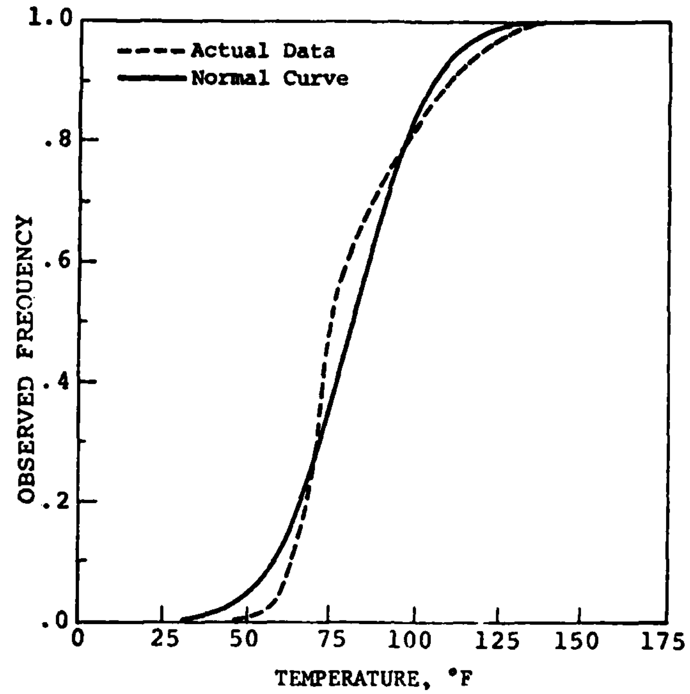


FIGURE 6. Normal Curve and Baseline of Thermal Standard, Top--Australia.

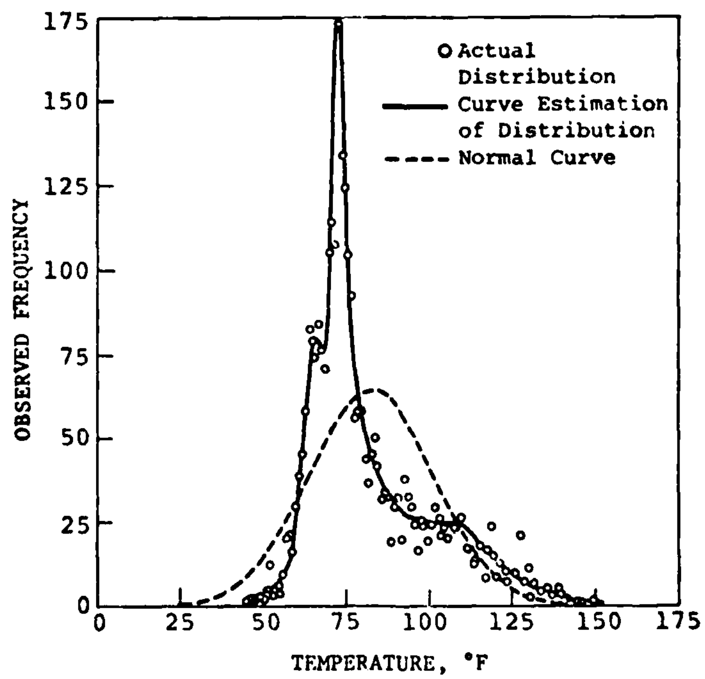


FIGURE 7. Observed Frequency Profile of Thermal Standard, Top and Normal--Australia.

## ABSORPTIVITY MEASUREMENTS

In order to use the thermal standard to predict ordnance temperatures, it was necessary to measure the absorptivity of the stainless steel surface. The method devised to measure this absorptivity is described. A thermocouple was welded to the inside top of each of two separate hemispheres. One of the hemispheres was blackened with a fuel-rich acetylene flame. The two hemispheres were placed in a shaded area and protected from the wind. Both indicated the same temperature. The shade was removed; both hemispheres were oriented so that they were facing the sun (convex side toward the sun), and temperature as a function of time was recorded for both.

Two methods were used to reduce these data to obtain the absorptivity. First, an energy balance on the metal near the thermocouple yielded

$$q_{sun}\alpha = \rho ct \left.\frac{dT}{d\tau}\right|_{\tau = 0}$$

where

$q_{sun}$ = heat from sun per unit area

$\alpha$ = absorptivity of object surface

$\rho$ = density of object

$c$ = specific heat

$t$ = thickness

$T$ = temperature

$\tau$ = time

This equation was true for both hemispheres; and, since $q_{sun}$, $\rho$, $c$, and $t$ were the same for both hemispheres,

$$\frac{\alpha_1}{\alpha_2} = \left.\frac{dT/d\tau_1}{dT/d\tau_2}\right|_{\tau = 0}$$

The estimate of $\alpha_1$ (the blackened surface) was 0.92; the two initial temperature-time slopes were measured, and $\alpha_2$ was calculated.

Second, at steady state the energy balance equation was

$$q_{sun}\alpha = h(T - T_{air})$$

where

h = convective heat transfer coefficient

If the assumption is made that the free convective heat transfer coefficient is the same for both hemispheres, then

$$\frac{\alpha_1}{\alpha_2} = \frac{T_1 - T_{air}}{T_2 - T_{air}}$$

Hence, $\alpha_2$ was again calculated.

The results of these relatively simple experiments indicated $\alpha$ to be 0.63 ± 0.06. The value finally used to make the *average* error zero in the prediction equation was 0.60. (Literature values for 304 stainless steel range from 0.4 to 0.66, depending on curing technique, etc. The literature was not very useful, except to show that the range of absorptivities covered the measured values.)

## RESULTS OF ANALYSIS

### CURVES OF CUMULATIVE PROBABILITY VERSUS TEMPERATURE

Cumulative probability versus temperature (CP-T) curves for the three general classifications of land types (arctic, temperate, and tropic) were described in detail in Ref. 1 (Part 4 of this report series). The three overall graphs (one for each zone) are presented in Figures 8 through 10.

When there is a need to combine the temperature distributions for some form of world-wide distribution, the recommended procedure is to take a weighted average of the 3$\sigma$ points and draw a straight line through the two points. Figure 11 shows the results for five different sets of weighting factors, as follows:

1. All three equally weighted
2. Land area weightings
3. Population weightings

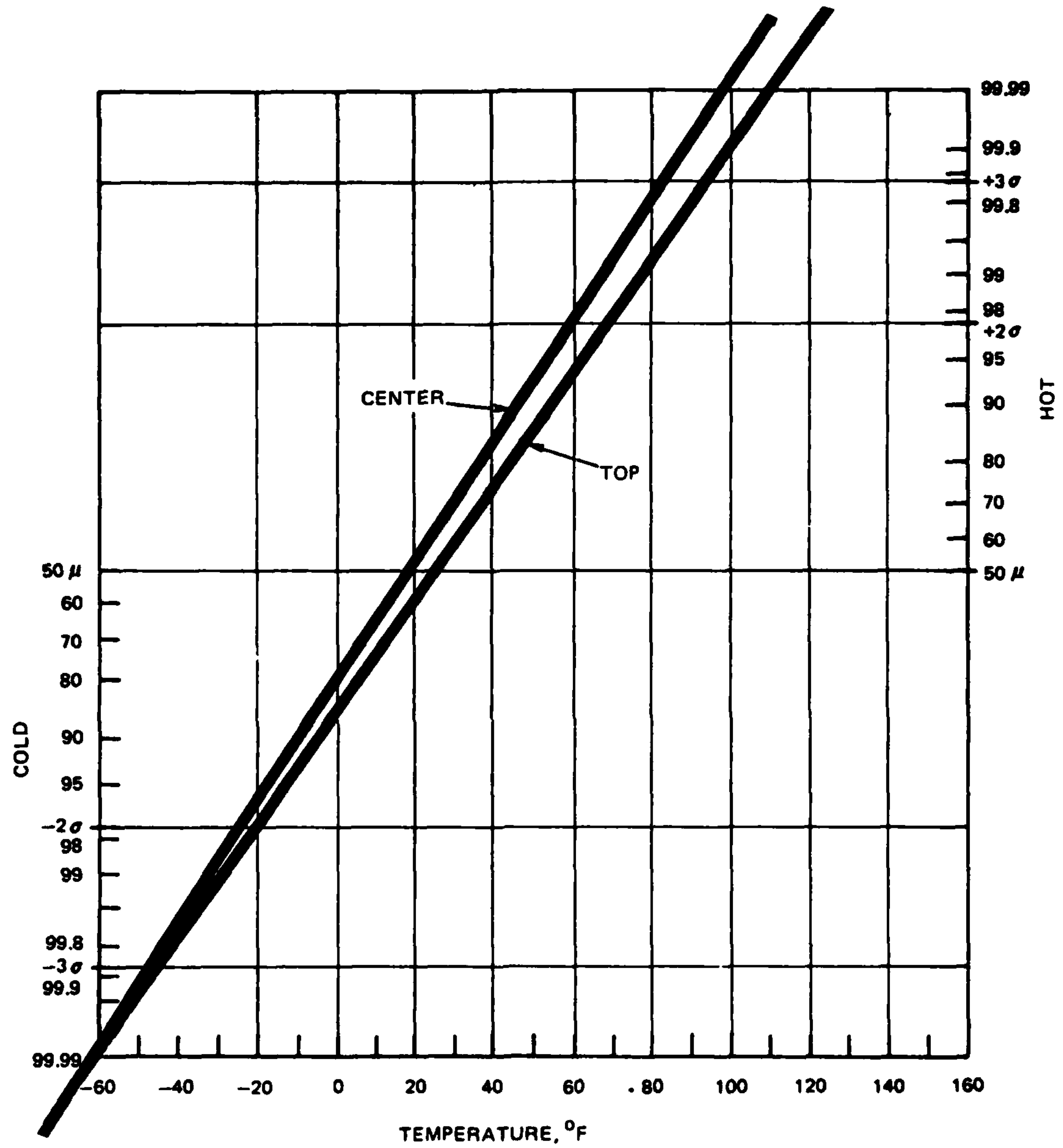


FIGURE 8. Cumulative Probability Versus Temperature, Arctic Zones.

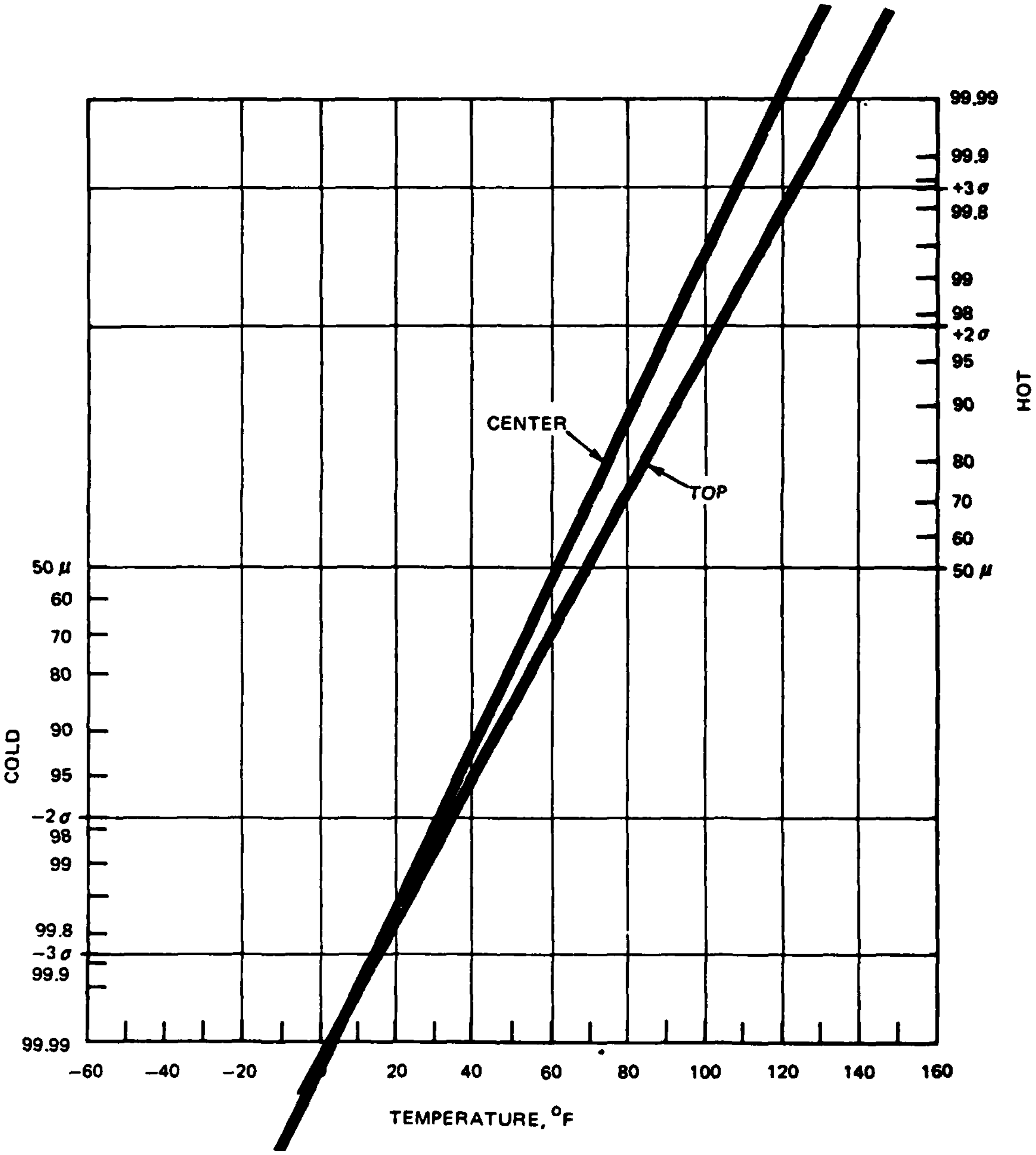


FIGURE 9. Cumulative Probability Versus Temperature, Temperate Zones.

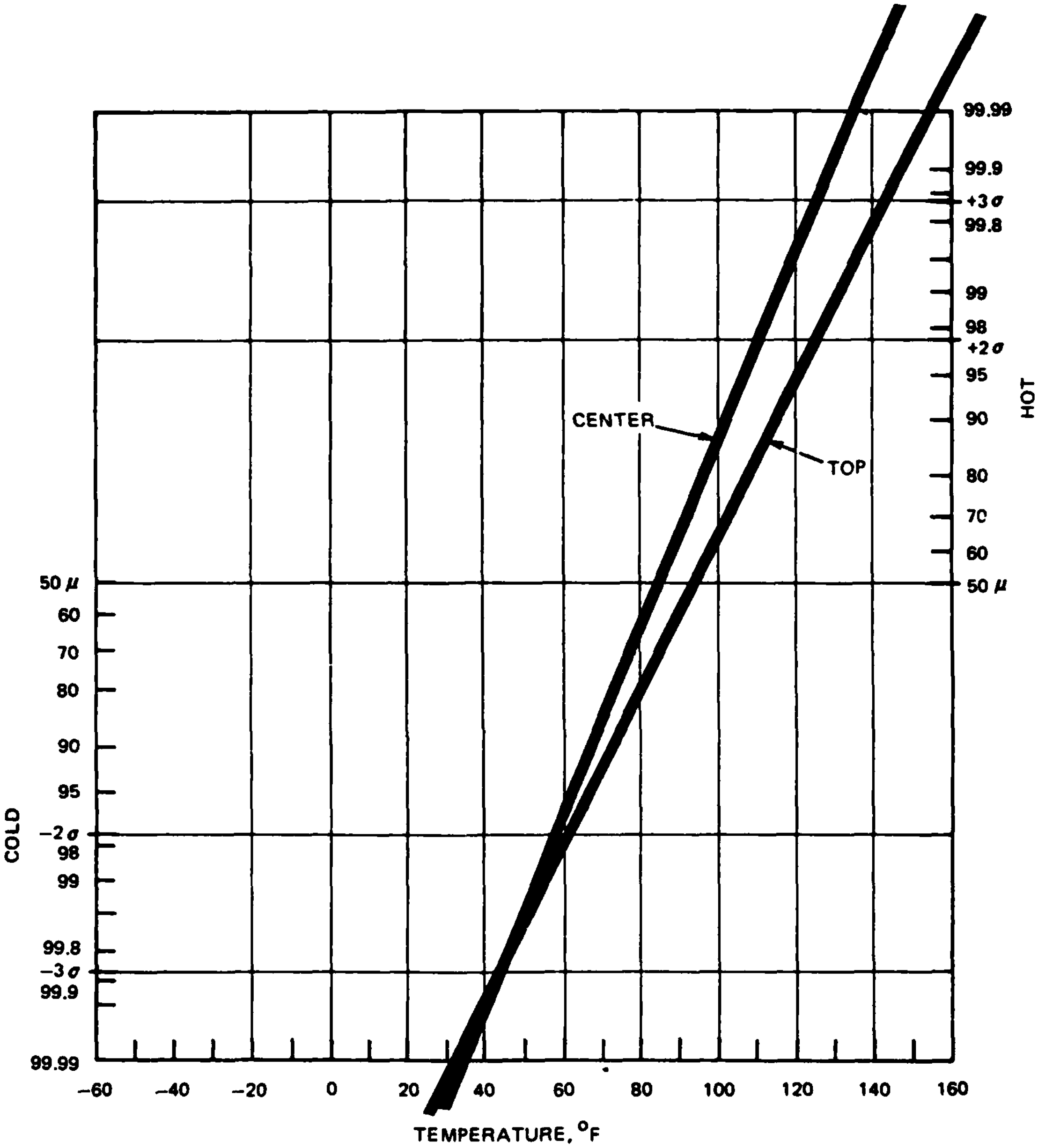


FIGURE 10. Cumulative Probability Versus Temperature, Tropic Zones.

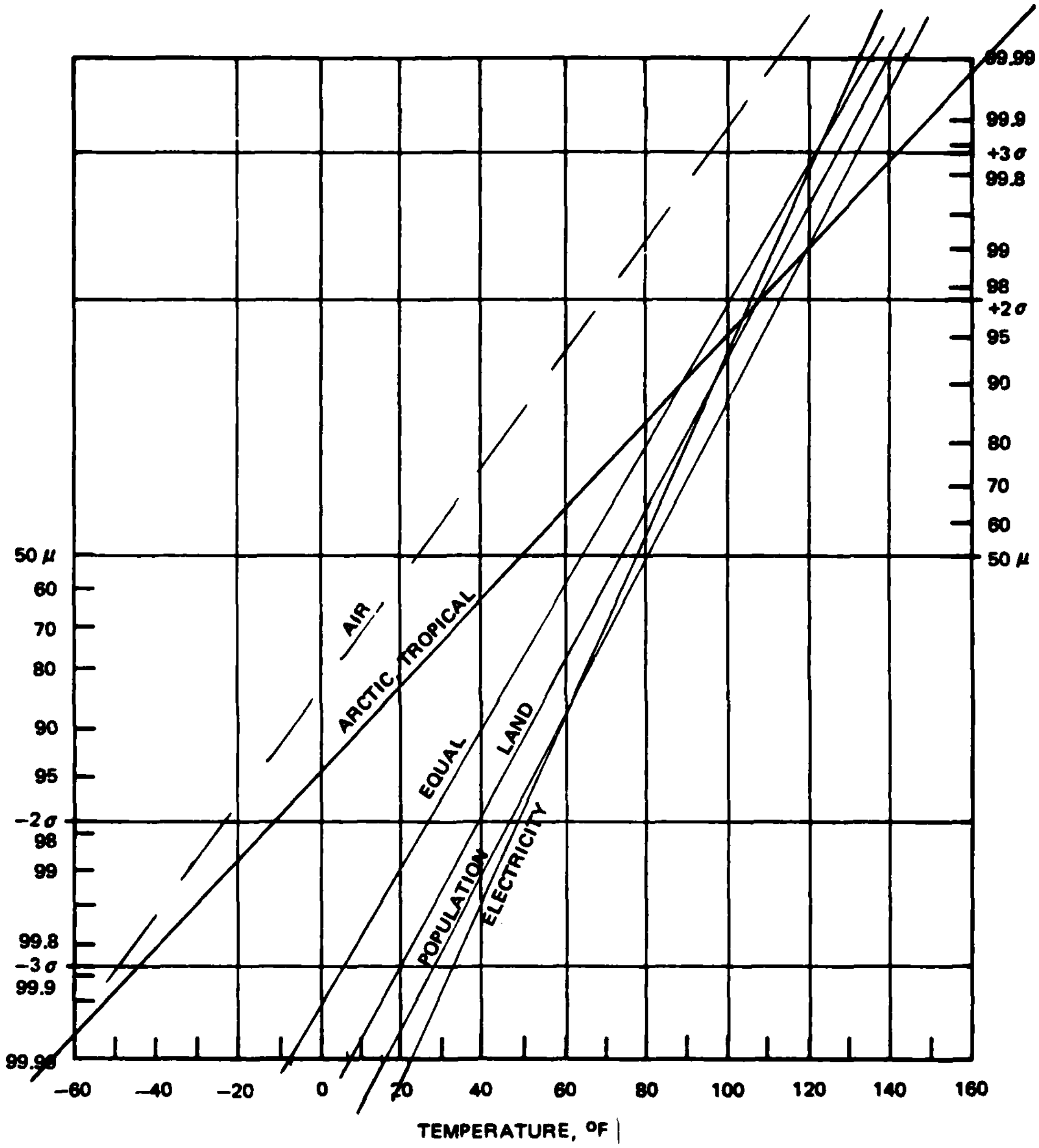


FIGURE 11. Cumulative Probability Versus Temperature, for Five Sets of Weighting Factors and for Air Temperature.

4. Power production weightings

5. $-3\sigma$ from arctic and $+3\sigma$ from tropical

Table 4 shows the weighting factors. A user would choose the weightings that best represent the areas of the world critical to the particular problem or object being developed or under consideration for design.

The graphs of Figures 8 through 10 were each developed using a few representative locations at which thermal standards had been stored and monitored for 2 to 10 years each. Each graph represents a normal distribution which is more conservative at the extremes than the actual temperatures ever observed. That is, the $+3\sigma$ and less likely high temperatures are higher on these figures than monitored in the field and the $-3\sigma$ temperatures are lower than observed in the field.

TABLE 4. Weighting Factors.

| Factor | Arctic zone | Temperate zone | Tropic zone | Weighted avg. temp., $^{o}F$, $-3\sigma$ ($+3\sigma$) |
|---|---|---|---|---|
| Land area | 0.14 | 0.47 | 0.39 | 18 (128) |
| Electricity production | 0.026 | 0.927 | 0.048 | 31 (124) |
| Population | 0.003 | 0.632 | 0.365 | 26 (131) |
| $-3\sigma$ | -44 | 15 | 46 | 5 |
| $+3\sigma$ | 95 | 124 | 144 | (121) |

AIR TEMPERATURE DISTRIBUTION

Very often, when world-wide temperature distribution curves for the thermal standard are to be used, there is a need to know the air temperature also. A detailed report by the U. S. Army Engineer Topographic Laboratories (as yet unpublished) gives a world-wide air temperature distribution taken from 100 locations well distributed throughout the world (see Appendix A). The $\pm3\sigma$ points were taken from this distribution, and straight lines were drawn through them, as shown in Figure 11. This shows the $-3\sigma$ point to be about the same as the cold thermal standard point of about $-46^{o}F$. The actual curve was not normal, but the normal approximation is again conservative at the extremes.

# COMPARISON OF PREDICTED AND MEASURED HOURLY TEMPERATURES

## PURPOSE

A series of measurements was made during the summer of 1974 at the NWC Salt Wells dump storage site, China Lake. The objective of these measurements was to obtain field data for comparison with predictions made by analytical techniques so one would know what types or size of prediction error could be expected. Temperatures were measured on Shrike and Sidewinder missiles in and out of their shipping containers. In addition, local meteorological conditions, such as ambient air temperature, solar radiation, wind speed, and relative humidity, were monitored for use as input for analytical predictions.

## PREDICTIVE METHODS

Three separate predictive techniques were evaluated: (1) analytical solutions which approximated the input conditions through the use of sine and step functions; (2) estimations of the thermal response of the ordnance of interest from the temperature history of a thermal standard (see Ref. 1, Part 1 of this report series), and (3) numerical computer solutions. Predictions were made by Professor T. E. Cooper of the Naval Postgraduate School, Monterey (analytical solution); Professor R. D. Ulrich of Brigham Young University (computer and thermal standard solutions); and C. F. Markarian of the NWC Aerothermodynamics Branch (computer solution).

These measurements and analytical predictions had three purposes: (1) evaluate the thermal standard as a tool for diurnal temperature predictions at specific locations on a variety of ordnance items; (2) compare the ability of the thermal standard with the ability of pure analysis, using meteorological data, to predict the same diurnal temperature variations; and (3) demonstrate the relative ease of comparison (i.e., time for making the calculations) using the thermal standard method.*

This series of experiments was designed and the analytical experts were commissioned (using their best-knowledge inputs) to predict the temperature response of several thermocouples at specific locations. The experts were given the hourly meteorological data for the several

*This was another of the critical field evaluations of the NWC thermal standard. If analytical techniques used by heat transfer experts can predict, for example, the thermal response of the top thermocouples on a Shrike rocket motor as well as the thermal standard, then the thermal standard might not be needed for that future purpose.

days needed, but they did not know the experimental results until after they had submitted their predictions. In order to make the thermal standard predictions, only the thermal standard temperature records were specified.[2]

For all of the predictive techniques, it was necessary to assume values for the absorptivity (of solar energy) of the ordnance or shipping container surfaces. Furthermore, the analytical techniques utilized additional assumptions that were based on prior art. The more sensitive assumptions were sky temperature, material properties, radial heat flow (one-dimensional only), sometimes no internal temperature gradients, etc. Each assumption induced error in the solution; hence, "exact" answers were not anticipated. Also, previous measurements on "identical" ordnance items instrumented with identical thermocouples did not yield "identical" thermal responses. The measured temperature on two different ordnance items at the same time of day sometimes varied as much as 6°F. Hence, two temperatures which are within 5°F of each other are considered to be virtually the same. Thus, prediction within 8-10°F of the measured values was considered to be very good. Of course, it would be expected that a few errors would be randomly higher or lower, but not consistently higher or lower; otherwise, one would expect to find a reason for error.

## ORDNANCE TEMPERATURE MEASUREMENTS

Temperature measurements for comparison with predictions were obtained on an AGM-45A-3 Shrike missile and an AIM-9H-2 Sidewinder missile. Both missiles had operational guidance control sections and simulated warheads and rocket motors. Desert sand was used as a simulant for the rocket motor grain. A plastic insulated the explosive in the warhead section of the Sidewinder. Both missiles were extensively instrumented with copper-constantan thermocouples. The missiles were exposed in an all-up configuration, although wings and fins were not installed.

Measurements were taken on the missiles both in and out of their standard shipping containers. The Shrike containers consisted of a Mk 399 Mod 0, light navy gray, steel, single-store shipping container and a three-missile shipping container with a white plastic top and gray aluminum bottom. The Sidewinder shipping container was white plastic and accommodated four missiles. During the sequence with containers, dummy missiles were used in addition to the instrumented missile in order to fill the containers, as would be the case in a storage situation. The containers were also instrumented with thermocouples.

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[2] Naval Weapons Center. *Diurnal Temperatures in Dump-Stored Missiles,* by Richard D. Ulrich and H. C. Schafer. China Lake, Calif., NWC, in process. (NWC TP 5923, publication UNCLASSIFIED.)

In addition to the ordnance temperature, various meteorological conditions, such as ambient air temperature, wind speed and direction, and relative humidity, were monitored at the measurement site. Solar radiation as measured by a pyroheliometer was obtained from the NWC Range Instrumentation Support Division. Data were recorded continuously throughout the summer of 1974. The dates selected for analysis and the corresponding missile configurations were:

| Date | Test Configuration |
|---|---|
| 12 June 1974 | Shrike out of container |
| 28 June 1974 | Shrike in single-store container |
| 29 August 1974 | Sidewinder out of container |
| 11 September 1974 | Shrike and Sidewinder in multi-store containers |

Details on the locations of all the thermocouples for all the measurements and details of the analysis are presented in Ref. 2.

## RESULTS AND DISCUSSION

The first results, for the all-up Shrike motor, are shown in Figures 12-15 for the top, bottom, east and west, respectively. Comparisons of the maximum and minimum temperatures and the times they occurred are shown in Table 5. The comparison of the three analytical methods indicates that the thermal standard was significantly more accurate overall in predicting the maximum values of ordnance response temperatures. It overpredicted the minimum temperature on the top of the round because the thermal standard was bare metal whereas the Shrike is painted. The paint has a very high emittance to the long wavelength radiation to the sky, whereas the bare metal emits very little at sky temperature wavelengths. The bottom and sides of the thermal standard were much better predicters of the minimum temperature for the missile.

Differences of $5^{o}F$ or less probably have no significance. That is, on a given day, predictions may be high or low by a few degrees, and that is as close as can be expected for prediction under any field circumstances. The low prediction of both Markarian and Cooper was attributable to the use of Brunt's equation for sky temperature. The reason for this attribution is that the results of both approaches were uniformly low for night as well as day temperatures. The Ulrich analytical prediction did not use Brunt's equation but used

$$T_{sky} = T_{air} - 20$$

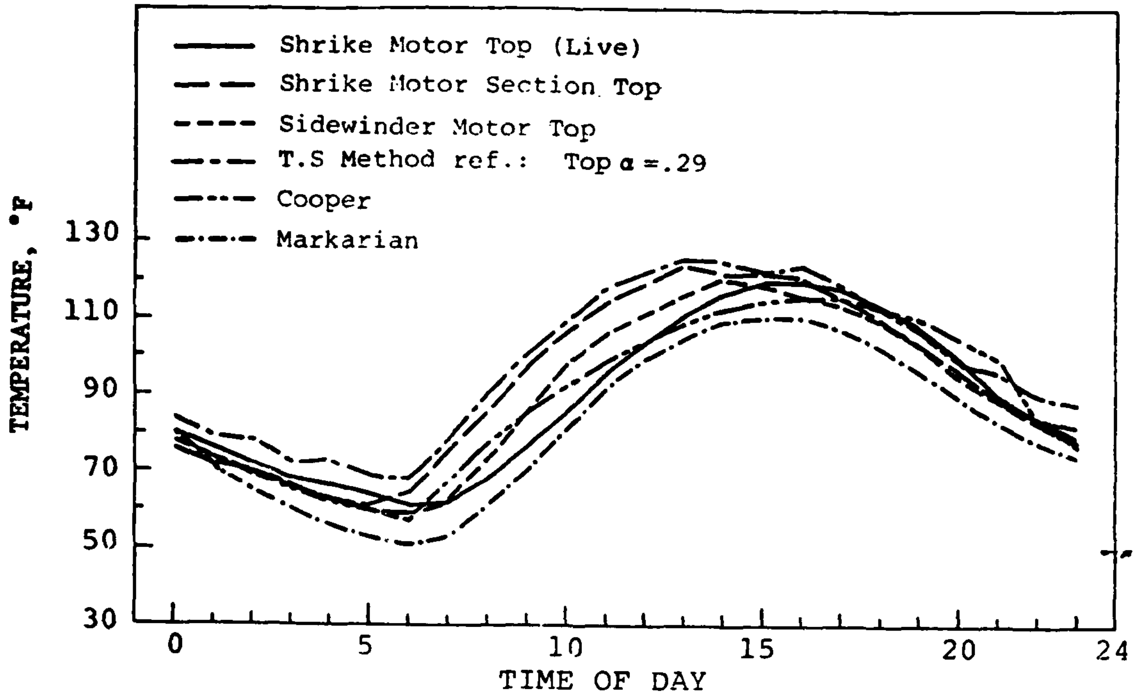


FIGURE 12. Comparison of Analytical Solutions With Shrike Top Experimental Temperatures (12 June 1974).

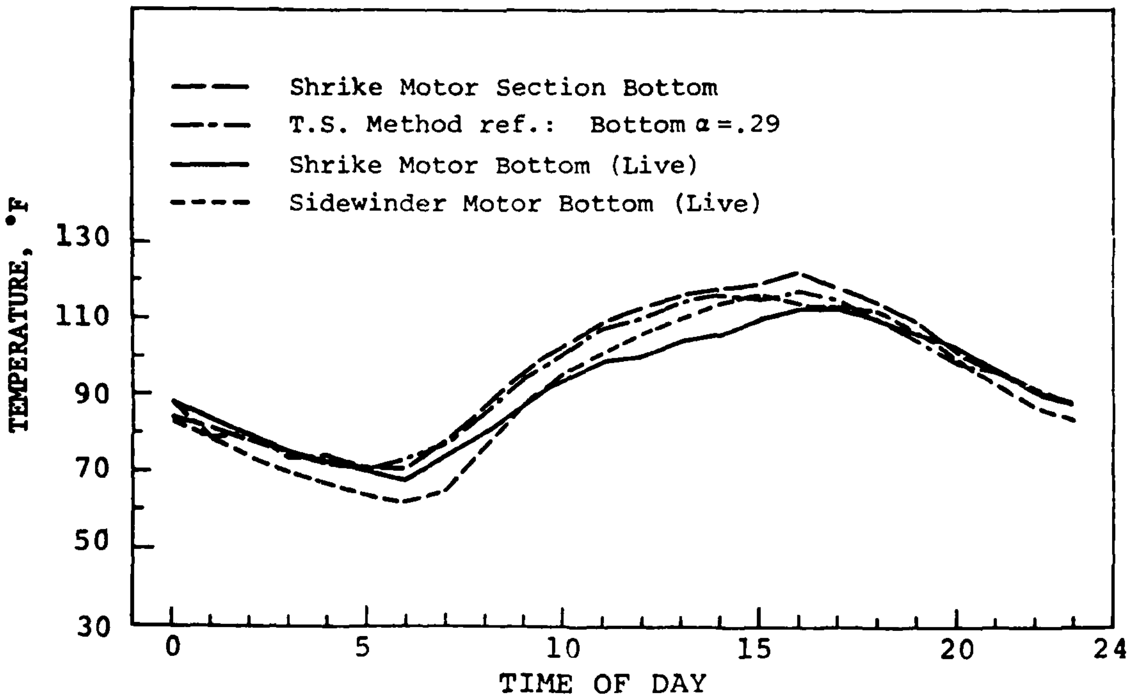


FIGURE 13. Comparison Using Thermal Standard Method--Shrike Bottom (12 June 1974).

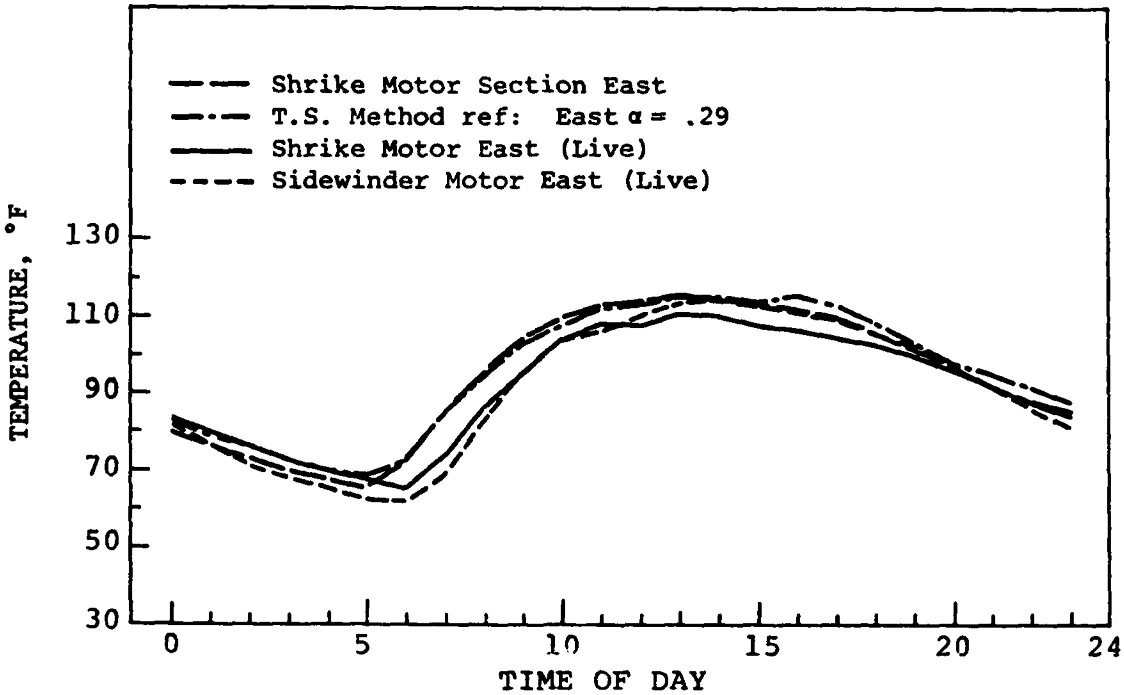


FIGURE 14. Comparison Using Thermal Standard Method--Shrike East (12 June 1974).

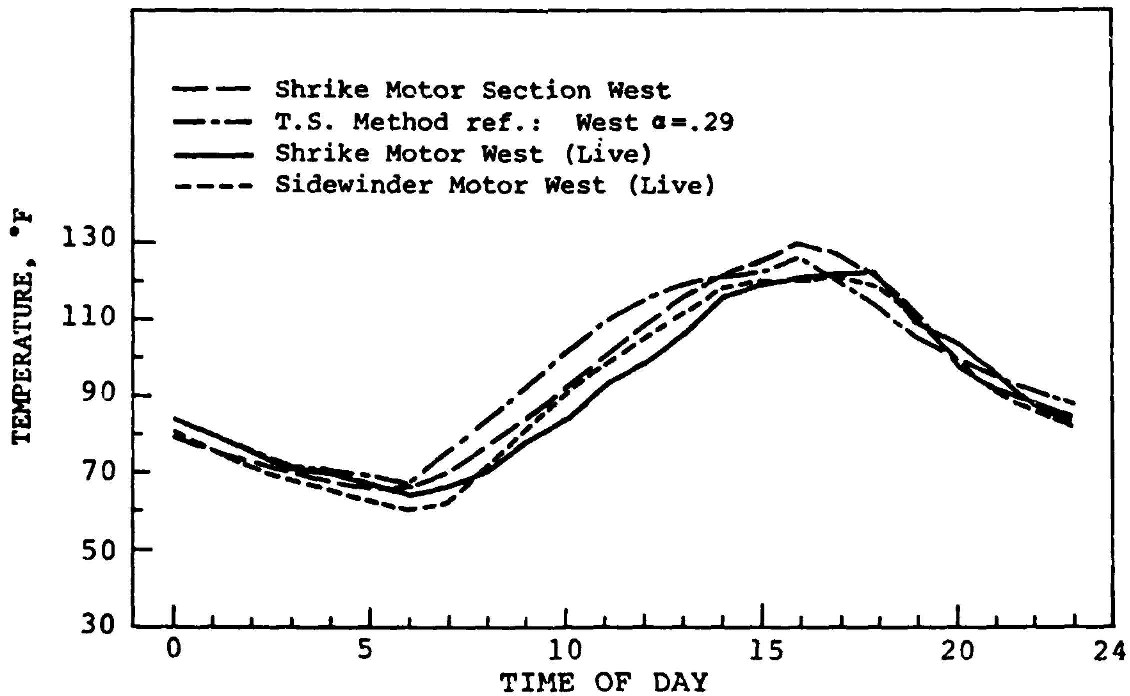


FIGURE 15. Comparison Using Thermal Standard Method--Shrike West (12 June 1974).

TABLE 5. Maximum and Minimum Temperature Comparisons.

| Data source | Top | | Bottom | | East | | West | |
|---|---|---|---|---|---|---|---|---|
| | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum |
| **Shrike (12 June 1974)** | | | | | | | | |
| Experimental | 123-1300 | 61-0500 | 122-1600 | 71-0500 | 116-1300 | 65-600 | 130-1600 | 66-0500 |
| Thermal standard | 125-1300 | 68-0600 | 117-1600 | 71-0500 | 116-1600 | 69-500 | 126-1600 | 67-0600 |
| Markarian | 110-1500 | 51-0600 | | | | | | |
| Cooper | 115-1700 | 57-0600 | | | | | | |
| Ulrich | 122-1400 | 60-0600 | 116-1700 | 72-0600 | 107-1200 | 65-0500 | 118-1600 | 64-0600 |
| **Shrike Container (28 June 1974)** | | | | | | | | |
| Experimental | 161-1400 | 54-0500 | 123-1800 | 65-0500 | 150-1100 | 56-0500 | 157-1400 | 56-0500 |
| Thermal standard | 156-1400 | 61-0500 | 127-1400 | 62-0500 | 133-1100 | 62-0500 | 151-1500 | 62-0500 |
| Markarian | 148-1400 | 38-0600 | | | | | | |
| Cooper | 125-1500 | 54-0300 | | | | | | |
| **All-up Sidewinder (29 August 1974)** | | | | | | | | |
| Experimental | 107-1500 | 56-0600 | 108-1500 | 62-0700 | 105-1500 | 60-0600 | 110-1600 | 59-0700 |
| Thermal standard | 111-1400 | 59-0600 | 105-1400 | 60-0600 | 104-1300 | 59-0600 | 111-1500 | 58-0600 |
| Cooper | 104-1600 | 58-0700 | | | | | | |
| **Multistore Container (11 September 1974)** | | | | | | | | |
| Experimental | 102-1500 | 61-0700 | 107-1600 | 69-0700 | No data | | 110-1600 | 63-0700 |
| Thermal standard | 111-1500 | 66-0700 | 109-1500 | 66-0700 | | | 118-1500 | 67-0700 |

whereas Brunt's equation gives the approximate valu.'s

$$T_{sky} = T_{air} - 60$$

The latter is much lower than justified by any China Lake data evaluation.

The data used in the thermal standard method were the thermal standard temperature responses and meteorological air temperatures. These two parameters, along with an assumed absorptivity ratio, are sufficient to predict any other surface temperature profile. The theoretical calculation methods used air temperature, humidity, wind velocity, solar radiation, and the assumed absorptivities (both short and long wavelength). This seems to give an advantage to the thermal standard method since it alone integrates all the thermal forcing functions into its own surface temperature. Its inherent capacity to store energy and conduct heat toward the center and back to the surface make it a true thermal integrator.

The method for prediction using the thermal standard was relatively simple compared to any of the analytical techniques. The temperature for any given time (for example, $T_{13}$) was

$$T_{13} = \left(T_{air}\right)_{13} + \left(T_{TS} - T_{air}\right)_{13} \frac{\alpha}{\alpha_{TS}} \tag{1}$$

This was repeated for each hour of the day, and the results were plotted for comparison. Not only can this method be done by hand, it is simple, fast, and, as can be seen, accurate.

This method uses less information (data) than the analytical methods; however, it has the advantage of being a "spy in the enemy's camp" whereas the analytical methods use information from instruments (wind, solar radiation, humidity) which can be viewed as "spies surrounding the camp."

The NWC Thermal standard prediction method was near the top maximum temperature for the Shrike container (28 June 1976) (see Figures 16-19 and Table 5). All the predictions were low. The thermal standard was low because the assumed $\alpha$ was too low; Markarian was low because Brunt's equation was used and because the assumed $\alpha$ was too low. Cooper was only predicting an average temperature, and this prediction was also low (125°F predicted, compared to 142°F experimental); again, the assumed $\alpha$ was probably too low. Both Markarian and Cooper used an $\alpha_{solar}$ of 0.6 and an $\alpha_{long}$ of 0.9. The thermal standard method used an $\alpha$ of 0.8. A real problem in this type of analytical or predictive work is a lack of knowledge of absorptive and radiative properties in general for particular items. There was a need for a low-cost instrument which

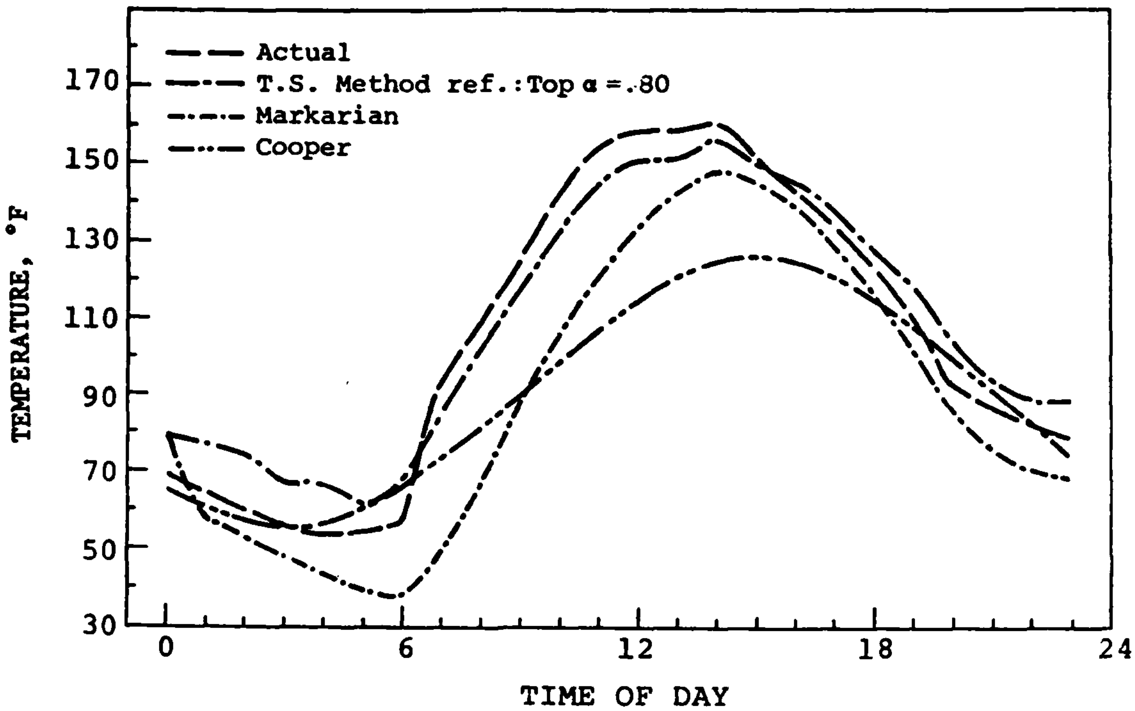


FIGURE 16. Comparison for Shrike Container Top (28 June 1974).

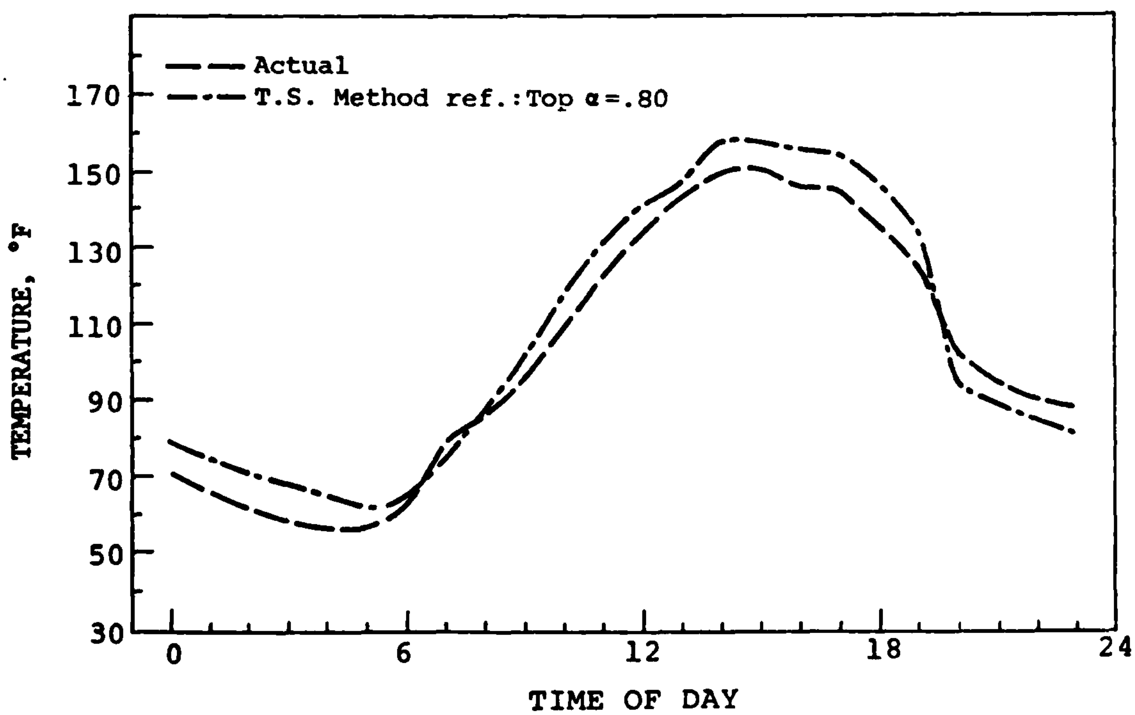


FIGURE 17. Comparison for Shrike Container West (28 June 1974).

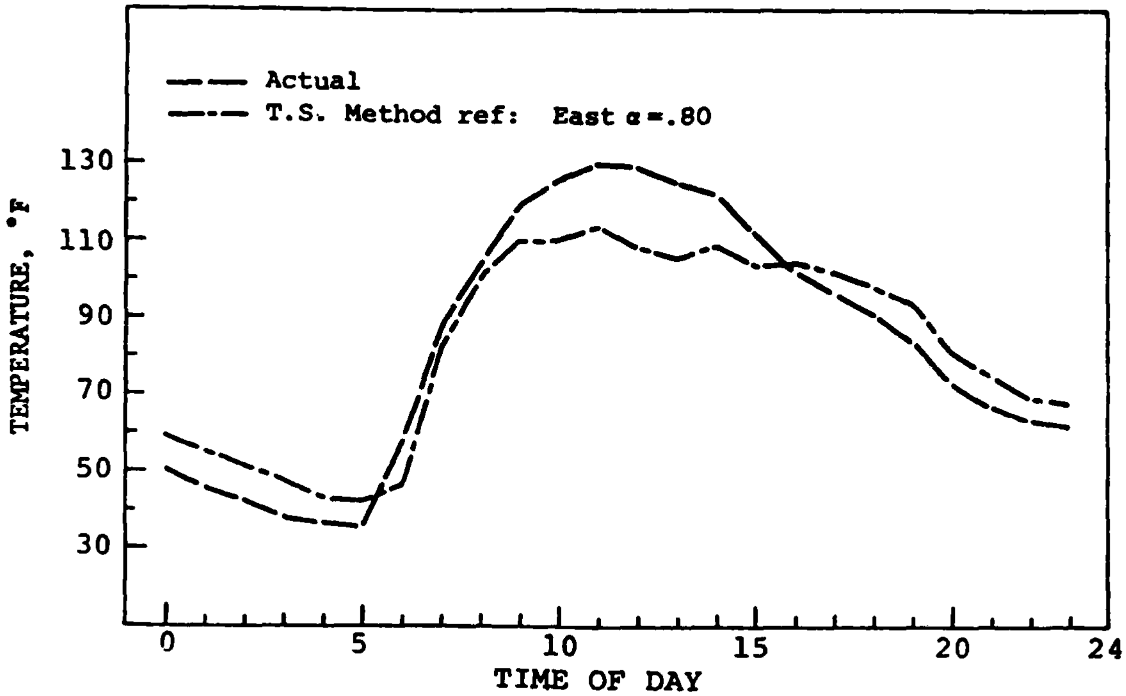


FIGURE 18. Comparison for Shrike Container East (28 June 1974).

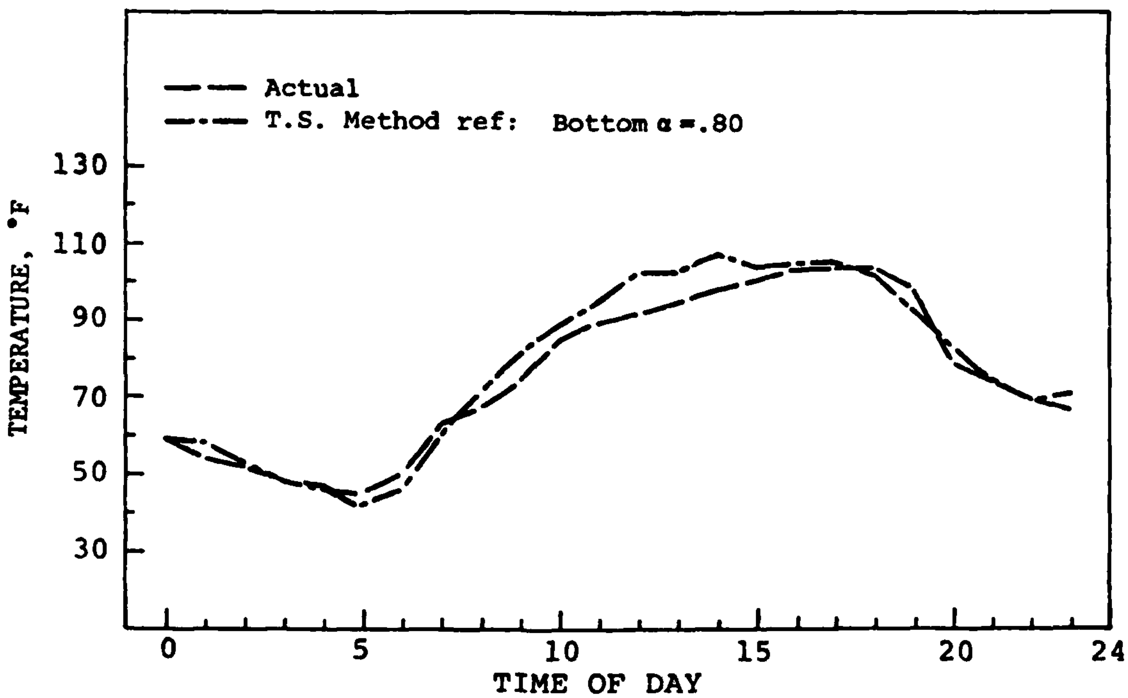


FIGURE 19. Comparison for Shrike Container Bottom (28 June 1974).

would measure these properties to the order of ±5-10%. This meter was developed for use, but not in time for these predictions.

The thermal standard prediction for the all-up Sidewinder (29 August 1974) (see Figures 20-23) had a maximum error of 4°F for all four positions and for maximum and minimum temperatures. This was considered to be an excellent comparison.

The predictions for the Shrike container, as shown in Figures 24-26, were all 1-9°F high. The reason for this is not known, but it may have been due to the transparent property of the plastic. It had been anticipated that, if any errors were present, they would be on the low side. This is because the low flat object should have a lower cooling heat transfer coefficient than the thermal standard.

The average error of all 30 thermal standard predictions (Table 5) is less than 1°F ($\sigma = 5$). There seems to be no general trend in the sign (+ or -) of the error. Based on predictions, in comparison with the other methods, the thermal standard is an excellent tool for ordnance temperature prediction and should be exploited further.

The preceding discussion has related mainly to rocket motors and in particular to motor skins. This was because the thermal standard was designed with rocket motors and warheads in mind. The comparisons that follow deal with other sections of the missile system, including the internal parts of the motor, guidance and computer sections, both skins and internal parts.

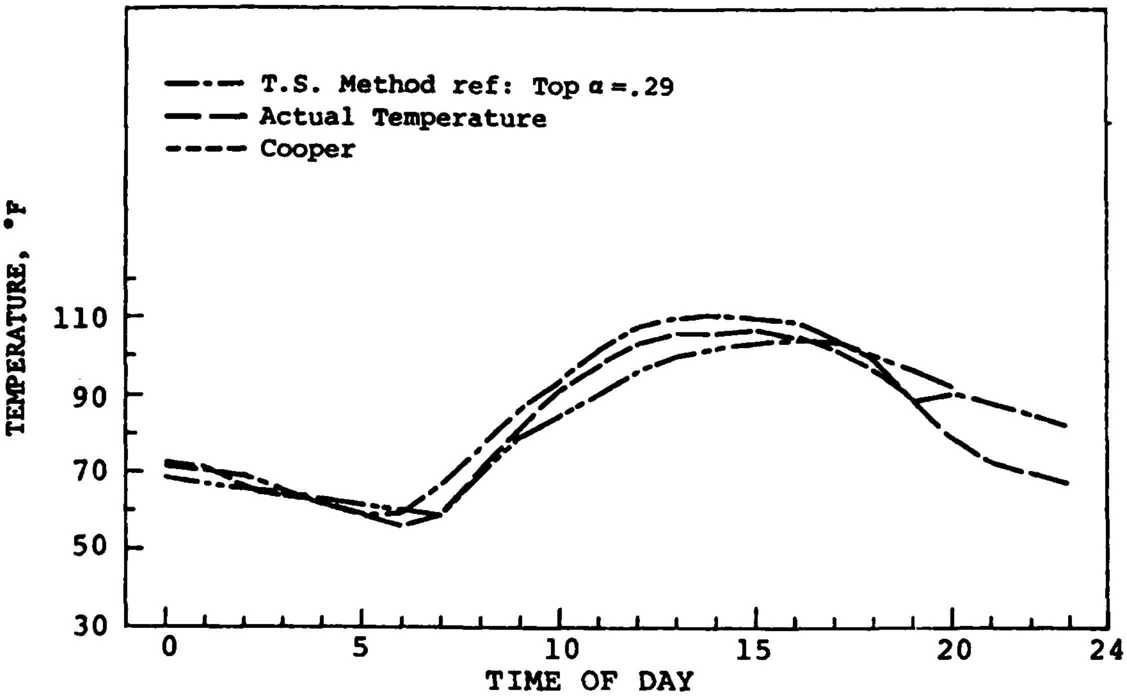


FIGURE 20. Comparison for Sidewinder Motor Top (29 August 1974).

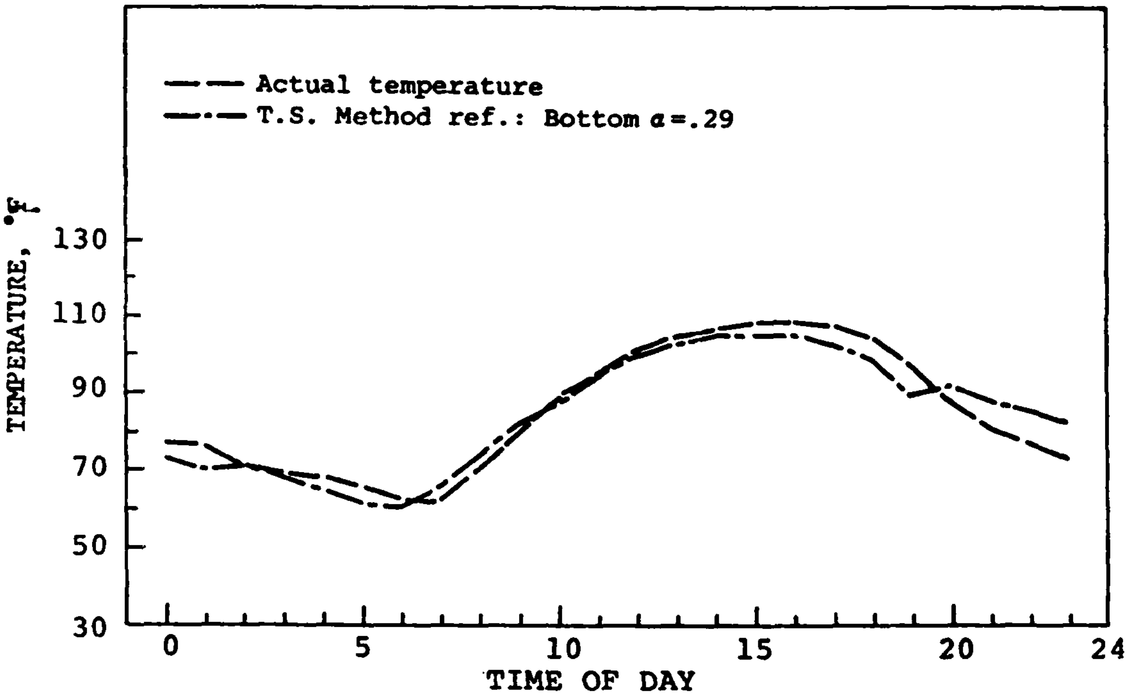


FIGURE 21. Comparison for Sidewinder Motor Bottom (29 August 1974).

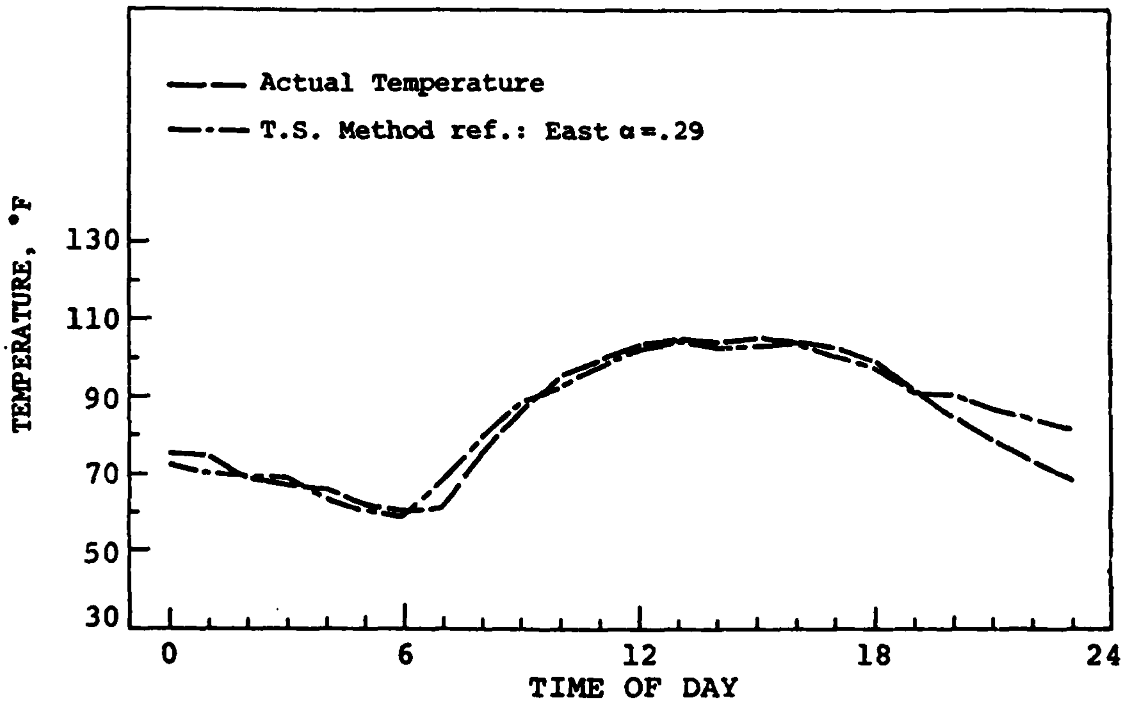


FIGURE 22. Comparison for Sidewinder Motor East (29 August 1974).

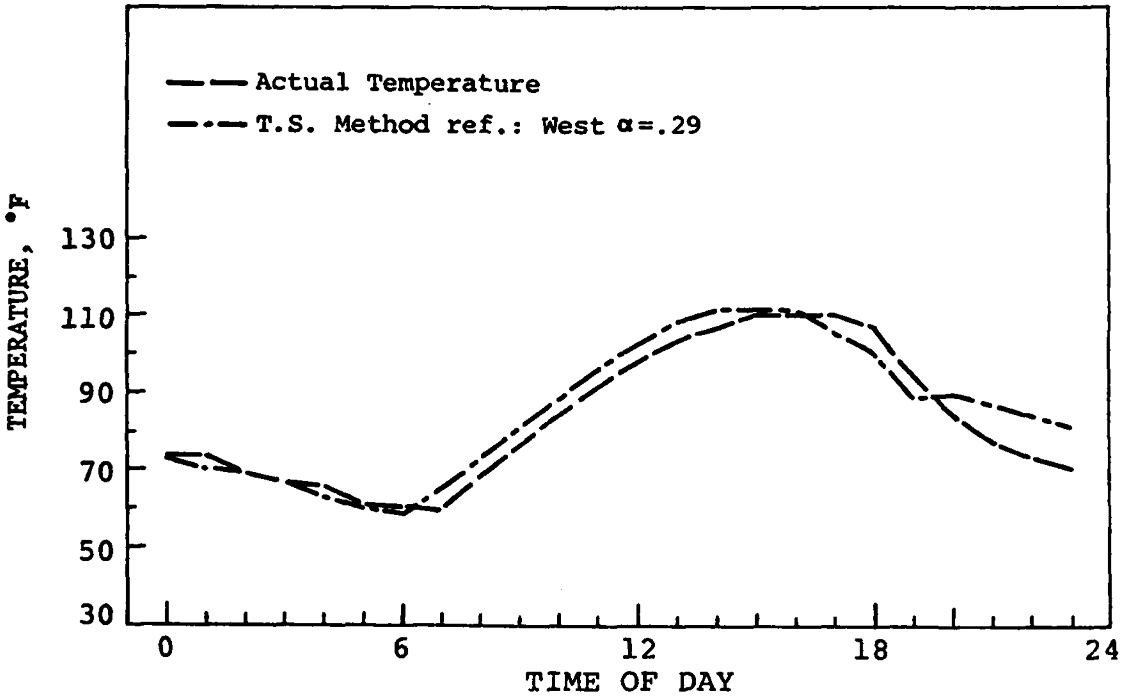


FIGURE 23. Comparison for Sidewinder Motor West (29 August 1974).

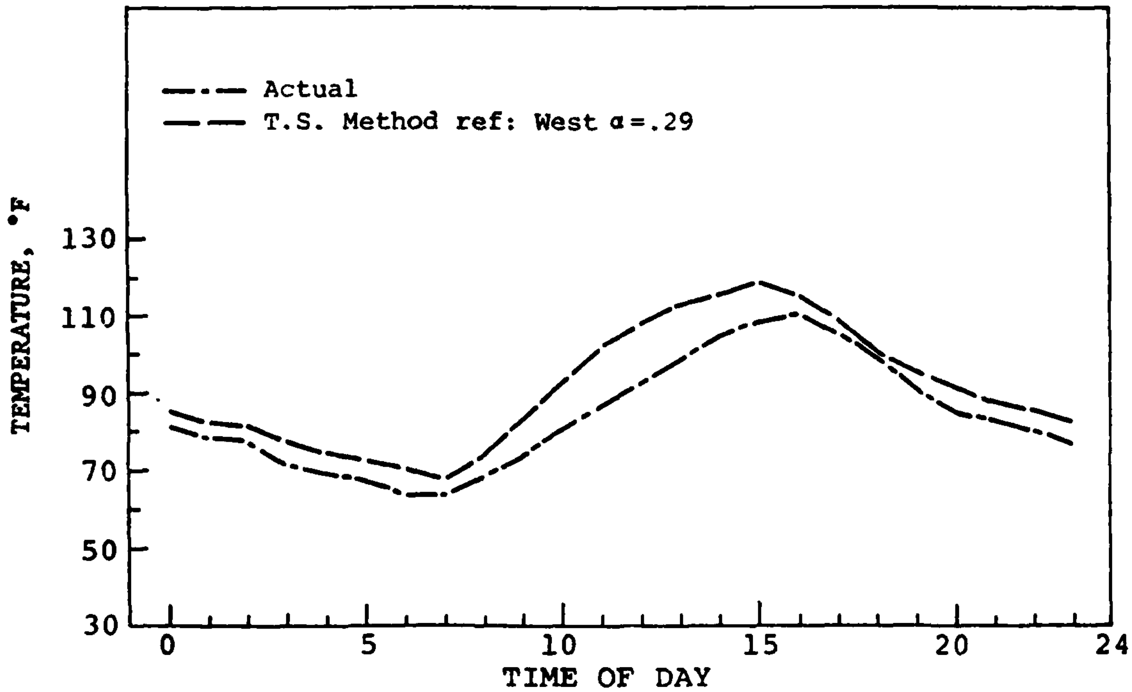


FIGURE 24. Comparison for Shrike Container West (11 September 1974).

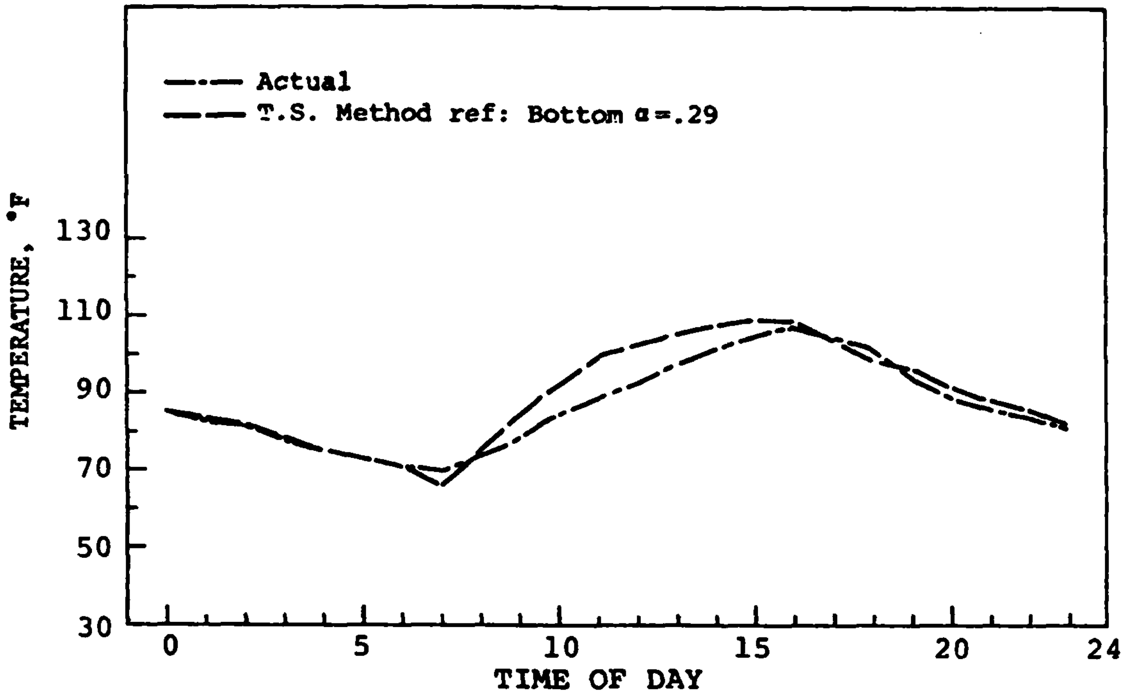


FIGURE 25. Comparison for Shrike Container Bottom (11 September 1974).

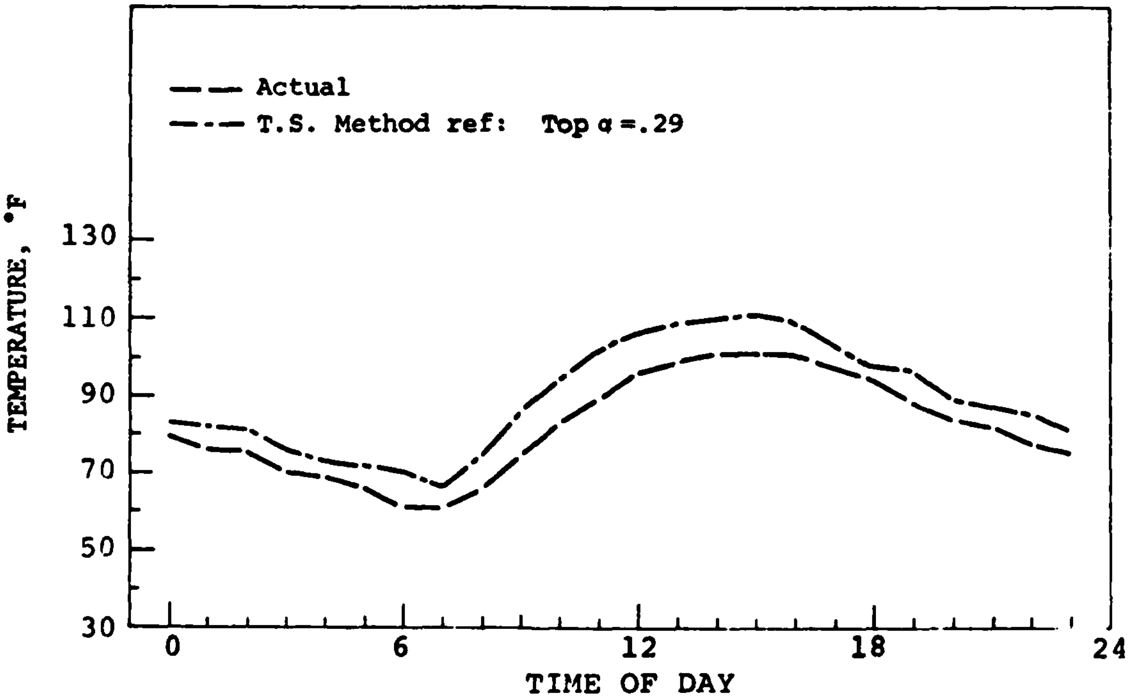


FIGURE 26. Comparison for Shrike Container Top (11 September 1974).

Figures 27-35 show these various comparisons. Where internal temperatures were predicted, the center thermocouple in the thermal standard was used in place of the surface thermocouples for surface prediction. Otherwise, the prediction equation was the same as Equation (1). Here again, these figures show very excellent agreement between the thermal standard prediction and the measured values. Some of the internal locations were also predicted analytically, as shown in Figures 30-32. The trends of the predicted curves are similar to the trends of the measured curves, but the peak temperatures are generally lower. This is probably due to the same problem observed in surface temperature prediction; i.e., the use of Brunt's equation for sky temperature calculations gave low predictions. It would be difficult to get good internal temperature predictions, since the internal temperature calculations depend on surface temperature calculations.

The Shrike container predictions were made using an assumed absorptivity for the container of 0.8. Figure 36 shows the effect of using 0.75 and 0.85 as compared to 0.8, as well as the actual curve. This shows a predicted maximum temperature rise of about $3^{o}$F for each 0.05 increase in the assumed absorptivity of a surface, which depends on the specific paint originally used, oxidation, or aging of the paint, corrosion, erosion, and other factors.

## USE OF CUMULATIVE PROBABILITY DATA

One method by which the enormous number of hourly data points can be presented is to plot the cumultive total of the hours that the thermal response was a certain temperature value or less. This has been done for all five thermocouples on a thermal standard and for the meteorological air temperature at several dump storage measurement sites for 1 or more years. Typical results are shown in Figure 37 for the Panama Canal zone. Some of the general features which are discussed relative to Figure 37 apply to all the warm climate thermal standard exposures. An object placed in a dump storage situation is generally warmer during the day than the free air because it receives its heat directly from the sun, whereas the air, being semitransparent, receives most of its heat by convection from the earth. The thermal response of the west side of an exposed item is either equal to or greater than that of the east side. However, the top of an exposed item generally will be slightly hotter than the west side with the peaks occurring at the same time. The center of an object never attains the extreme high temperatures of the surface because it is protected from the extreme exposure by the outside. Generally, for most of the night (about half of the total time), all the temperatures are about the same. In the cold arctic regions where there is little solar energy, all the temperatures are about the same. This is especially true for the temperatures below the 0.5 cumulative probability point.

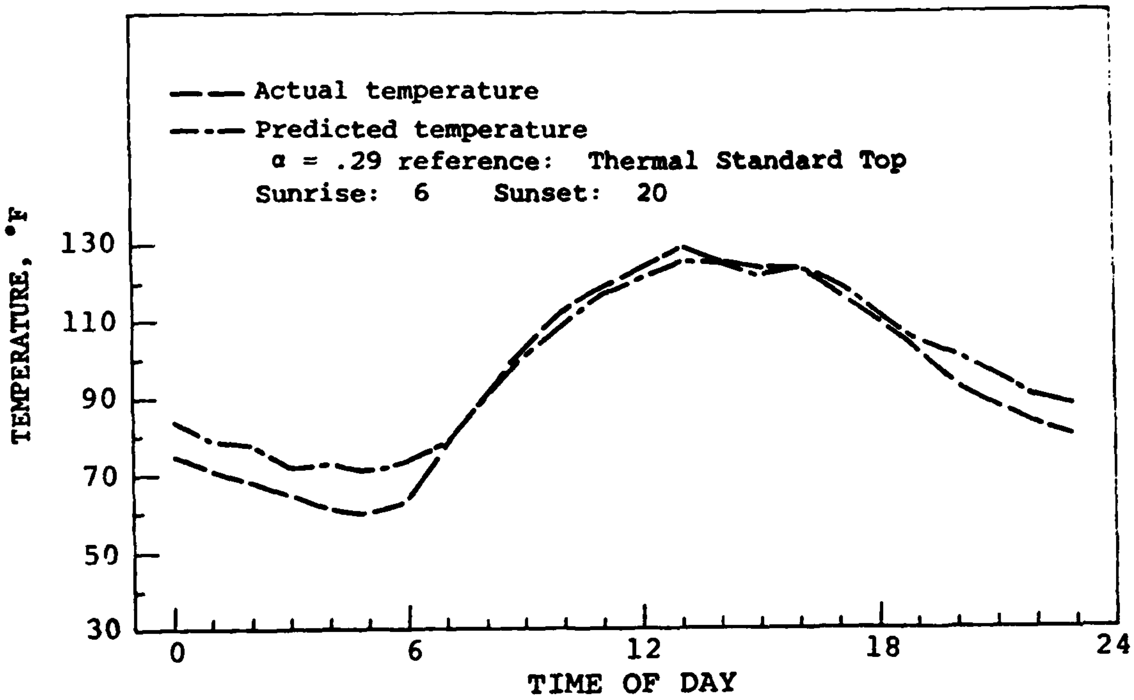


FIGURE 27. Comparison for Shrike Control Section Top Skin (12 June 1974).

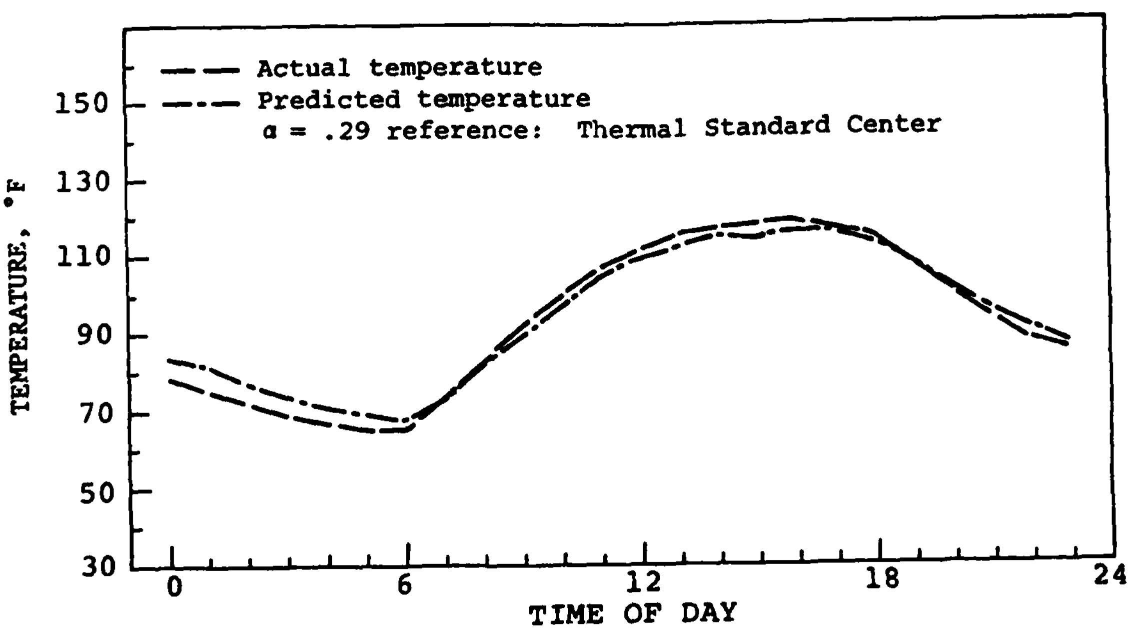


FIGURE 28. Comparison for Shrike Computer Section Top Skin (12 June 1974).

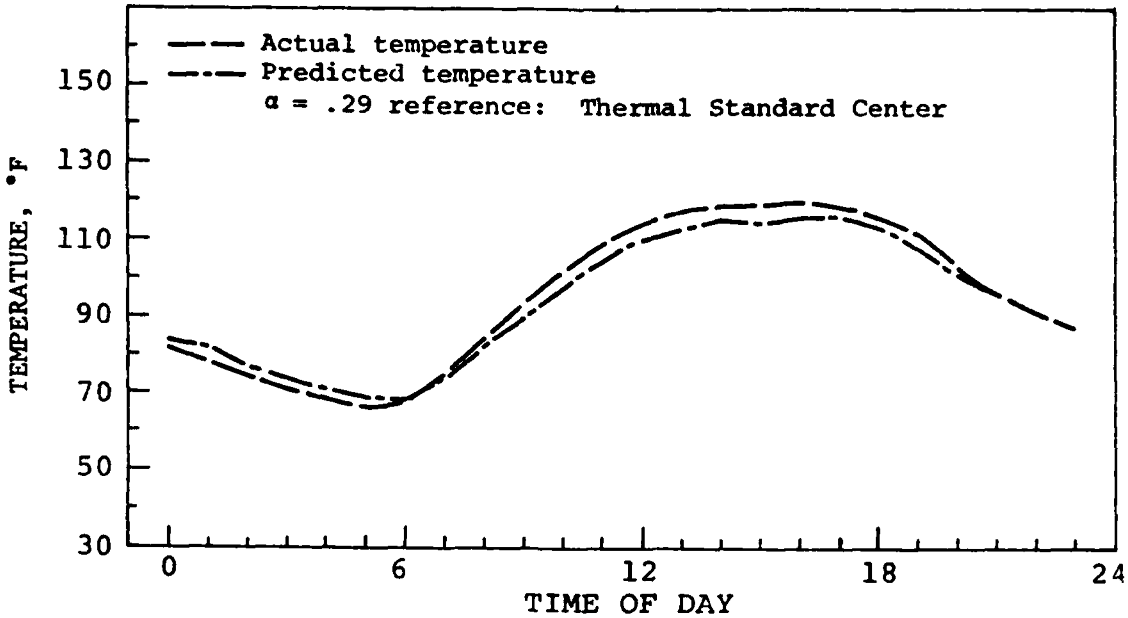


FIGURE 29. Comparison for Shrike Control Section Center Steel Bulkhead (12 June 1974).

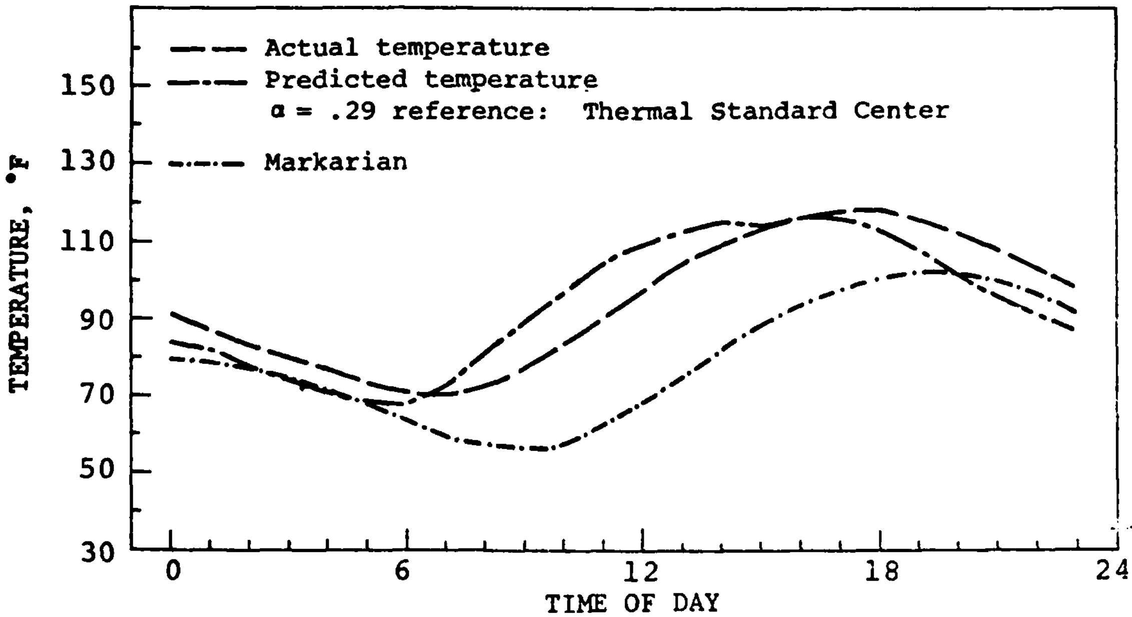


FIGURE 30. Comparison for Center of Shrike Motor Section (12 June 1974).

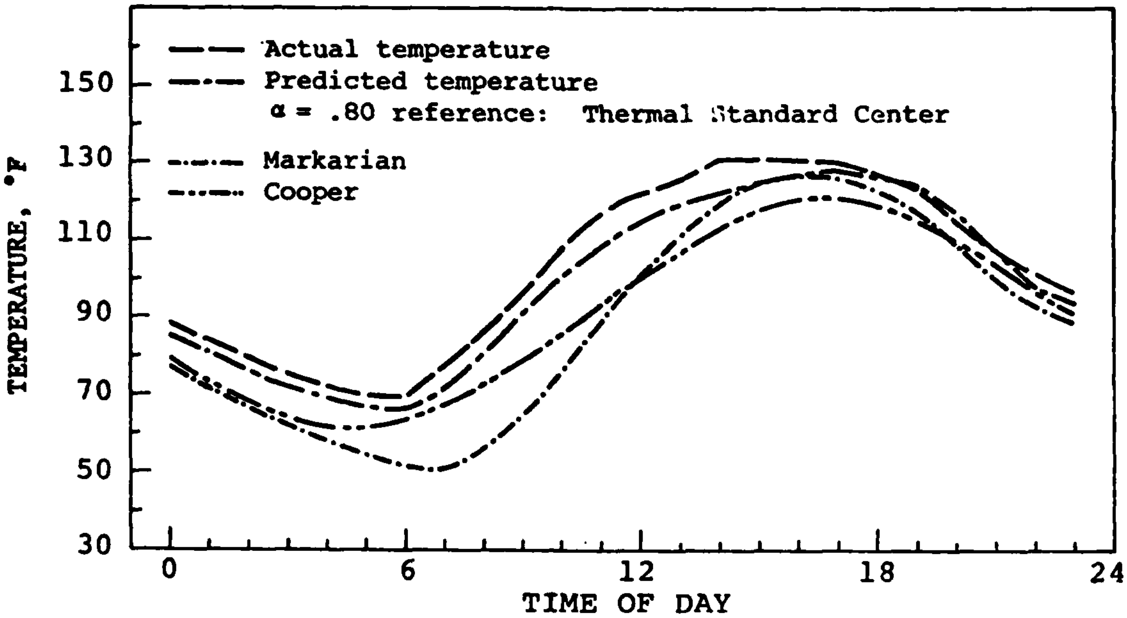


FIGURE 31. Comparison for Shrike Motor Top in Mk 399 Container (28 June 1974).

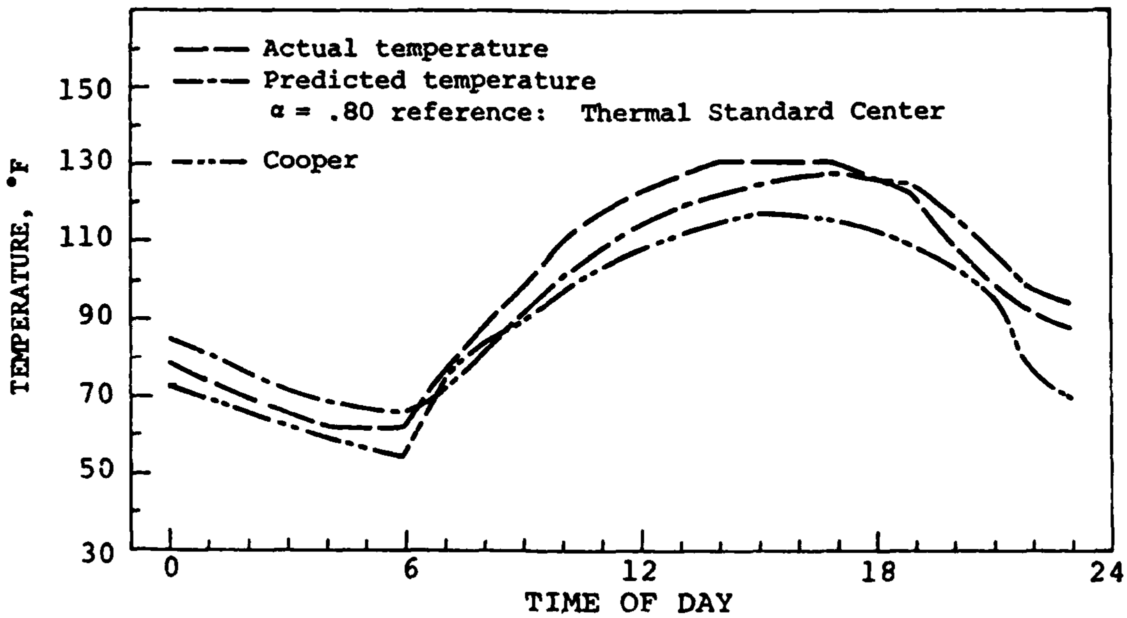


FIGURE 32. Comparison for Shrike Guidance Section Top Mk 399 Container (28 June 1974).

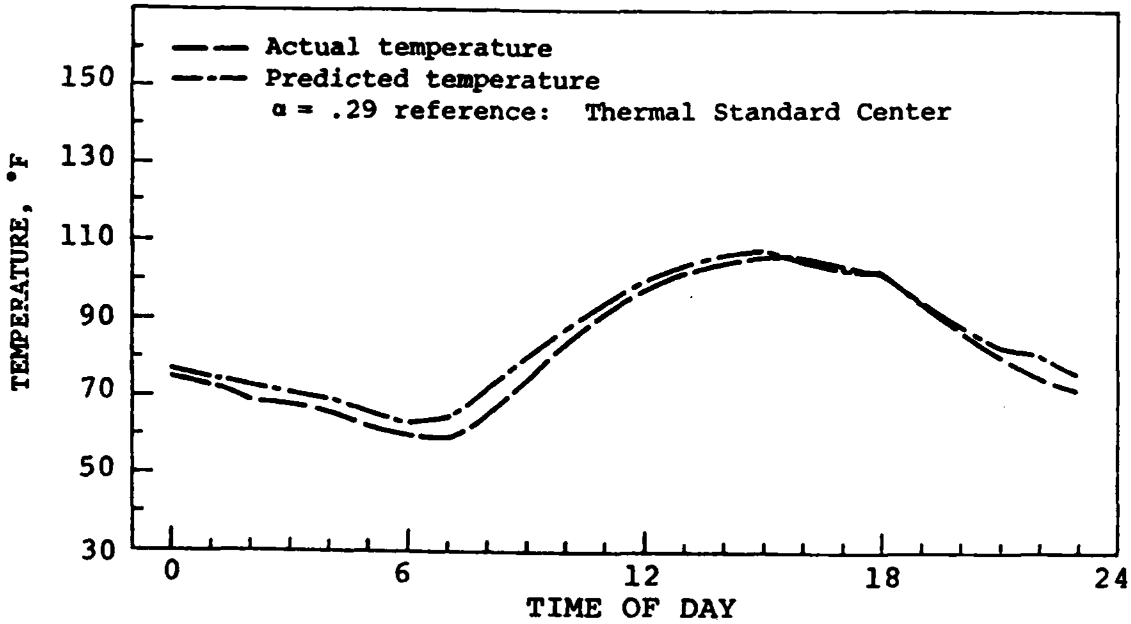


FIGURE 33. Comparison for Sidewinder Motor Section Center.

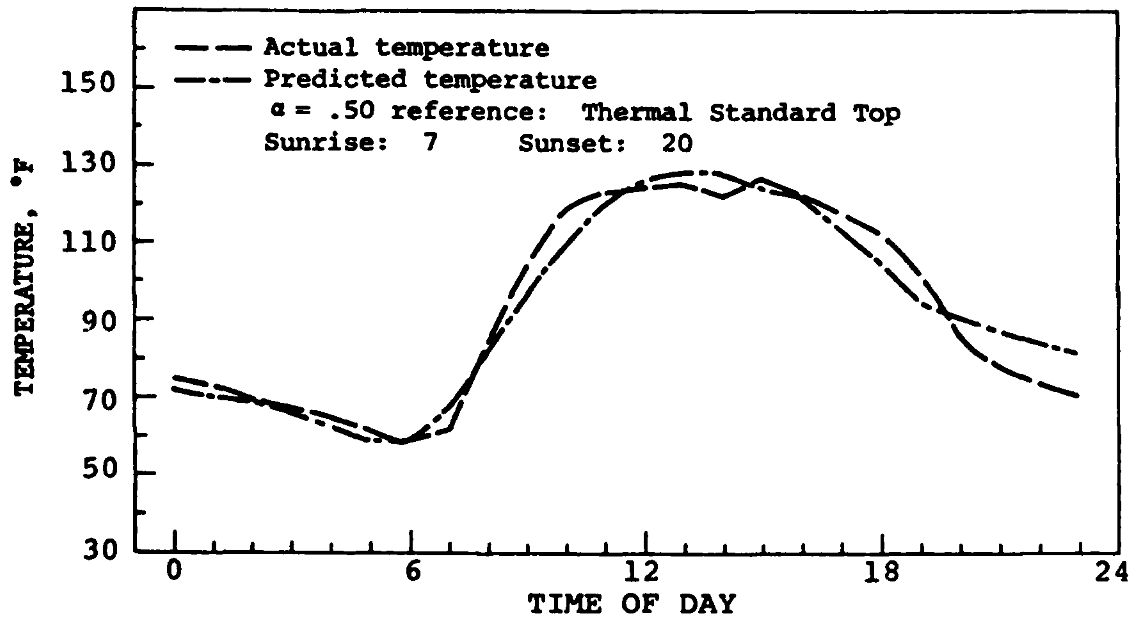


FIGURE 34. Comparison for Sidewinder Control Section Top Skin (29 August 1974).

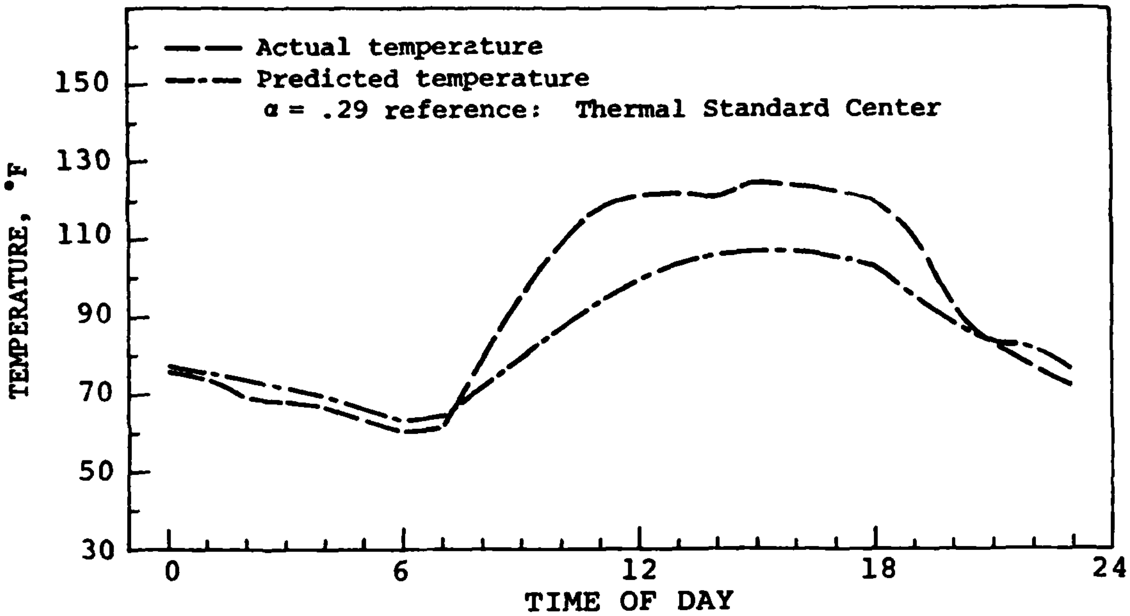


FIGURE 35. Comparison for Sidewinder Control Section Plastic Surface of Module (29 August 1974).

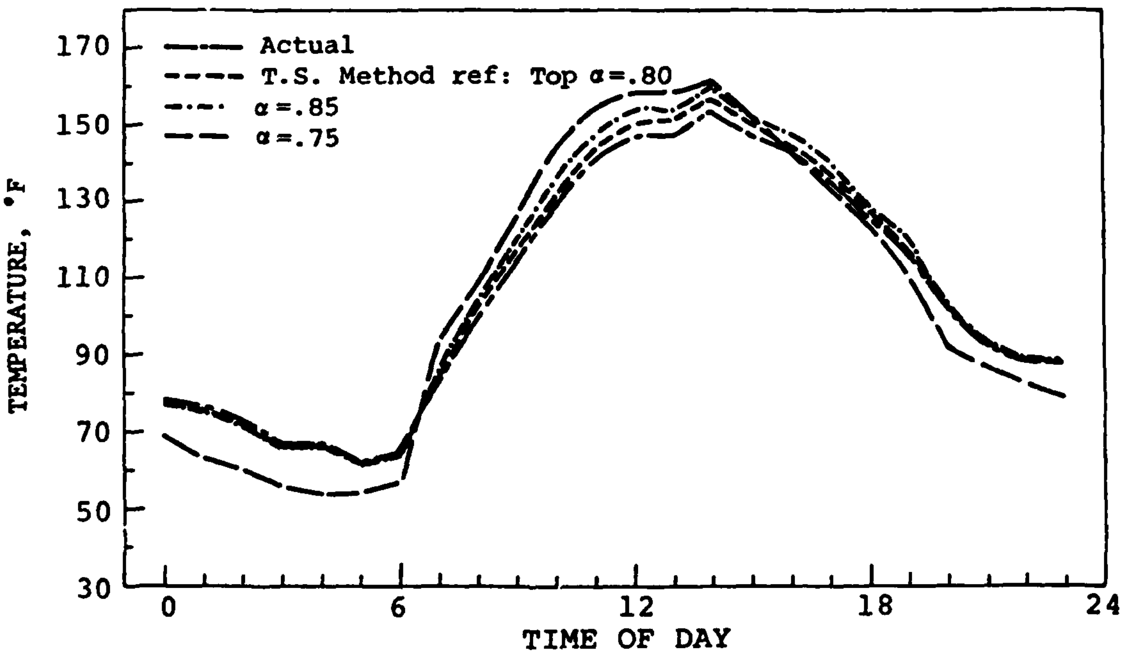


FIGURE 36. Comparison for All-up Shrike Container Top.

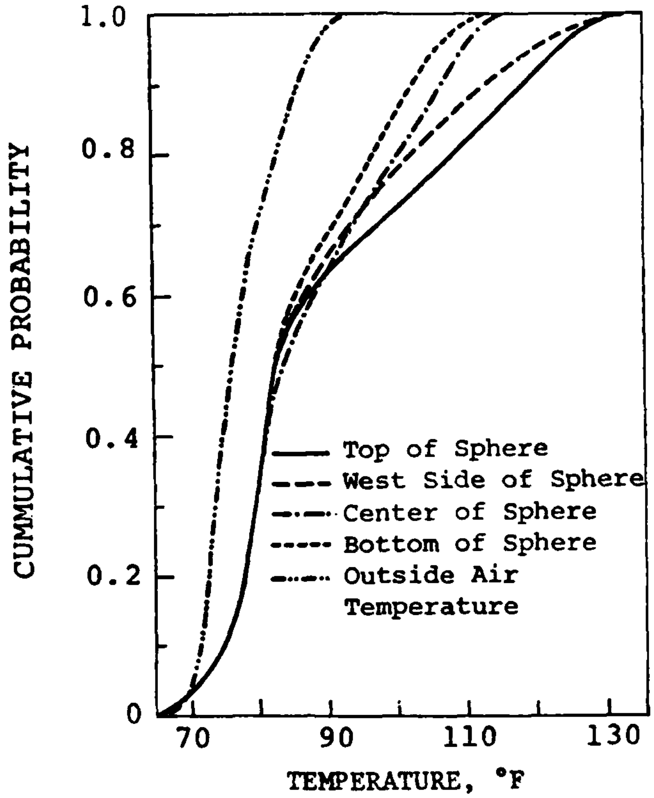


FIGURE 37. Thermal Standard
Panama Canal Zone, 1971-72.

While this cumulative-probability format does not give the daily temperature profiles of an object, it does give a method for estimating annual extremes and distributions and delineates the range of temperatures that exists any specified percentage of the time. The cumultive probability versus temperature format is useful in making economic trade-off studies for the design of weapons that are to operate in both hot and cold, or world-wide, environments. Obviously, no weapon is designed for a given day; it is designed to function over a wide range of daily thermal situations. Since this connotes a statistical sample of daily situations on a world-wide scale, the probability of occurrence must be addressed. The designer, as an engineer, is interested only in the probability of occurrence of those environmental situations that can be expected to happen with the weapon being designed. For example, if the weapon is being designed for a reliability of 95% (or less), then probable chance-of-occurrence temperature response values of one in a billion are not appropriate, even though they can be projected to be possible.

Therefore, the cumulative probable chance-of-occurrence of temperature data gives the designer a variety of "extremes" and a statistical context in which they are appropriate. (This approach is in the spirit and context of DoD Directive 5000.40.)

## CONCLUSIONS

1. Data from five locations representative of the temperate zones of the earth have been gathered, reduced, and analyzed. The cumulative data from the top thermocouple of the thermal standard are well represented by a normal distribution curve having a mean of 69°F and a standard deviation of 18.3°F. The thermal standard center thermocouple is well represented by a normal curve having a mean of 63°F and a standard deviation of 15.7°F.

2. Data from four locations representative of the arctic zones of the earth have been gathered, reduced, and analyzed. The cumulative data from the top thermocouple of the thermal standard are well represented by a normal distribution curve having a mean of 26°F and a standard deviation of 22°F. The thermal standard center thermocouple is well represented by a normal curve having a mean of 23°F and a standard deviation of 20.5°F.

3. Data from six locations representative of the hot zones of the earth have been gathered, reduced, and analyzed. The cumulative data from the top thermocouple of the thermal standard are well represented by a normal distribution curve having a mean of 92°F and a standard deviation of 18°F. The thermal standard center thermocouple is well represented by a normal curve having a mean of 86°F and a standard deviation of 14°F.

4. Cumulative probability versus temperature is a good method of condensing an enormous amount of data, and it can be used by missile systems designers.

5. The typical day for the thermal standard plus only 72 data points (every tenth day maximum and minimum temperatures) gives an accurate estimate for cumulative probability versus temperature curves.

6. The thermal standard method of predicting diurnal temperature variations for various locations on ordnance is simpler and more accurate than the analytical methods used by heat transfer experts.

# RECOMMENDATIONS

The thermal standard is a neophyte as a tool in thermal environment instrumentation. However, its value has been demonstrated in a few areas, as described in this report. Some recommendations for additional future applications are mentioned below.

1. A large number of thermal standards should be placed in various locations at which any possible future ordnance storage might be projected. This will provide design information for future generations of naval weapons. So far, only a few extreme locations have been sampled. The new locations should include each continent and a variety of climates which are common to that continent. Some emphasis should be given also to isolated strategic locations.

The results will probably fall into a relatively few general patterns, and then the map of the earth can be marked according to these patterns. Possibly, this can be done in conjunction with existing weather stations.

These thermal standards would not need monitoring indefinitely, but only for a few years in each location. This would be sufficient to give the desired engineering design information.

2. The thermal standard concept may be useful in predicting temperature responses of items larger than typical naval ordnance, such as airplanes, ships, antennas, or even buildings.

3. The thermal standard could be used as a control device in environmental test chambers. That is, if the thermal standard is forced through a particular time-temperature curve as derived in the field, other adjacent ordnance may be expected to go through a simulated field experience. This is true only if the chamber is primarily a radiation oven and secondarily a convection oven. Also, the radiation control must be such that sun movement could be simulated. Most currently used environmental chambers do not have this capability.

4. The thermal standard center temperature might be a better indicator of "degree days" as used in heating and air conditioning design work than air temperature.

# Appendix A

## FREQUENCY DISTRIBUTION OF AIR TEMPERATURES NEAR THE SURFACE OF THE EARTH OUTSIDE OF ANTARCTICA

This appendix contains data extracted from a paper by Richard D. Sands of the U. S. Army Engineer Topographic Laboratories and is used here with his permission.[3]

[3] U. S. Army Engineer Topographic Laboratories. *Frequency Distribution of Air Temperatures Near the Surface of the Earth Outside of Antarctica*, by Richard D. Sands. Fort Belvoir, Va., 25 October 1978. (ETL-GS-A, publication UNCLASSIFIED.)

1. Background and Summary: The work described in this study is the first part of an attempt to find a better basis for establishing climatic design criteria. The intent was to develop a single set of figures to represent the annual frequency of occurrence of the whole range of temperatures expected throughout the world, which is defined as all the land areas exclusive of Antarctica. The result is a synthetic cumulative frequency curve made up of average data (not extremes) from stations representing all of the climatic regimes. As for interpretation, the curve, of course, represents no single place; but, if place is treated as a random variable, the curve is a fairly reliable representation of the relative frequency of various temperatures. Stated another way, it is a reasonable representation of the annual relative frequency of the world-wide range of temperature.

There is no intention at present to try to use this composite temperature curve as a substitute for the design values now in use. One reason is that place probably should not be treated as a random variable. Another is that the degree of risk one should assume is partially a function of the equipment itself.

The end result of this preliminary effort is a temperature frequency curve that can be described by the values in Table A-1 or, graphically, by the curve in Figure A-1. The remainder of this report is intended as a record of the sampling strategy and methodology used in deriving the curve.

2. Sampling Strategy: The sampling strategy employed consisted of the following: First a Koppen-Geiger regionalization scheme with map was selected which reflected the greatest relationship to world temperature regimes as they were known. Then these climatic regions were plotted on an equal-area projection. Next, the area in square area units for each climatic area on each continent was obtained and totaled by continent (see Table A-2). By dividing by 100, one could then see where one, more than one, or less than one station was required. In order to approximately represent each and every 1% of the earth's land surface, station location would have to be made so that no more than 100 station averages would be required.

3. Data Base: Finding data to fit the sampling distribution of meteorological stations was not unusually difficult. This is because the sampling strategy allowed substitution by either type-of-climate or by location within the same general climatic area. It even became possible to use multiple stations in some difficult-to-represent areas (such as the Mediterranean region and in northwestern Europe by combining the frequency distributions of two stations in differing kinds of

locations. These particular combined frequencies of two stations were then divided by two for a single total for the area.*

4. Data Transformations: Changing the data into a standard 5-degree temperature class interval was done where necessary. This caused the splitting of some 2-degree temperature categories in half. Another required transformation was to first convert all data used to the standard number of hourly observations for each calendar month, regardless of the length of record, missing observations, or the number of times per day observations were made. This "normalized" the data for each station to 8766; i.e., the average number of hourly observations in 1 year (Table A-3). Totally synthetic data were used for only 1% of the earth's surface; i.e., the Tibetan Highlands. Wherever data from another continent were used (as in the case of three stations for the interior of Brazil and two other instances in Africa), the frequency distribution was modified slightly before the substitute location and data were added to the tally sheet prior to obtaining the grand totals. Modifications were based on a comparison of maximum and minimum data. Also, one station in southern Arabia was used twice to count for 2% of the earth's land surface in the general region.

As much care as possible was taken to avoid selecting an unrepresentative station for a whole region where a choice of stations was available. This was done by checking available published maps of frequencies of extremes of high and low temperatures for the continent or region.

*Two stations were used in 19 different instances. Therefore, the total of stations utilized numbered more than 100.

TABLE A-1. Frequency Distribution of World Air Temperatures.

| Temperature class, °F | Total observations | Cumulative frequency, % |
|---|---|---|
| -70/-66 | 4.0 | 0.0005 |
| -65/-61 | 51.2 | 0.0063 |
| -60/-56 | 166.7 | 0.0253 |
| -55/-51 | 535.4 | 0.0864 |
| -50/-46 | 685.6 | 0.1646 |
| -45/-41 | 1516.2 | 0.3376 |
| -40/-36 | 2347.2 | 0.6052 |
| -35/-31 | 3111.5 | 0.9603 |
| -30/-26 | 4383.2 | 1.46 |
| -25/-21 | 4573.2 | 1.98 |
| -20/-16 | 6087.0 | 2.68 |
| -15/-11 | 7292.5 | 3.51 |
| -10/-06 | 8045.7 | 4.43 |
| -05/-01 | 9620.9 | 5.3 |
| 000/004 | 10191.0 | 6.5 |
| 05/09 | 10921.0 | 7.7 |
| 10/14 | 13267.6 | 9.2 |
| 15/19 | 15210.4 | 11.0 |
| 20/24 | 16237.7 | 12.8 |
| 25/29 | 23811.9 | 15.5 |
| 30/34 | 33055.5 | 19.3 |
| 35/39 | 32689.0 | 23.0 |
| 40/44 | 30630.0 | 26.5 |
| 45/49 | 38711.5 | 30.9 |
| 50/54 | 47017.5 | 36.3 |
| 55/59 | 53808.5 | 42.4 |
| 60/64 | 63364.9 | 49.7 |
| 65/69 | 66820.7 | 57.3 |
| 70/74 | 86488.6 | 67.2 |
| 75/79 | 92994.3 | 77.8 |
| 80/84 | 85603.7 | 87.5 |
| 85/89 | 54419.5 | 93.7 |
| 90/94 | 28358.5 | 97.0 |
| 94/99 | 14738.3 | 98.7 |
| 100/104 | 7088.3 | 99.465 |
| 105/109 | 3358.5 | 99.848 |
| 110/114 | 1148.2 | 99.979 |
| 115/119 | 175.2 | 99.999 |
| 120/124 | 9.0 | 100.000 |
| | 876600.0* | |

*876600 is the net result of utilizing 100 sampling areas and adjusting all data within each sampling area to a base of 8766, or the number of hours in an average year.

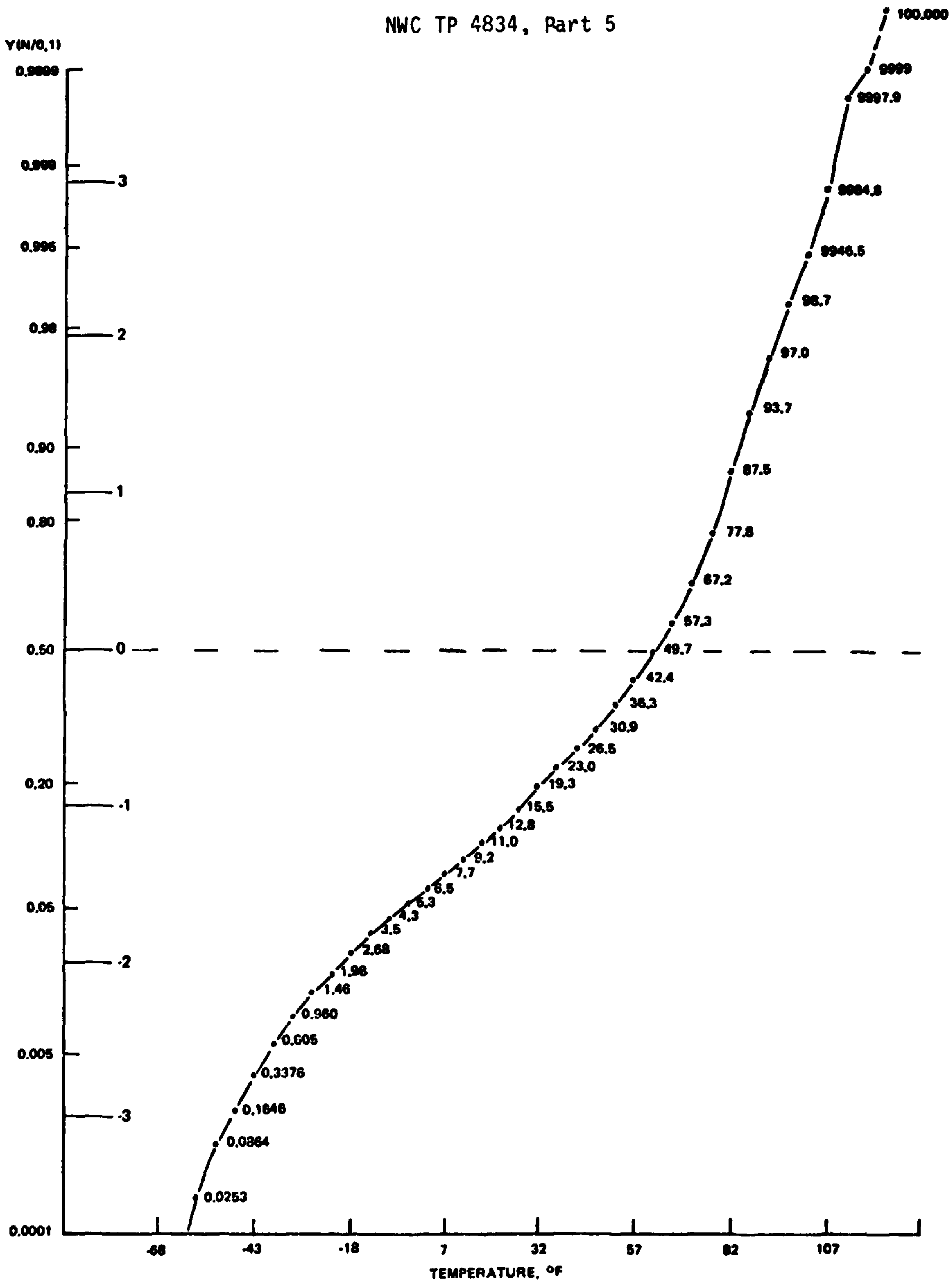


FIGURE A-1. Annual Frequency of World-Wide Temperatures.

TABLE A-2. Summary of Station Sample Planning.

| Type of climate | Total world area | No. of stations to cover | Area in square units | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | North America | Greenland | South America | Eurasia | Africa | Australia/ Oceania |
| Af/Am | 267 | 7 | 14 | | 100 | 80 | 48 | 25 |
| Aw | 523 | 13 | 26 | | 197 | 62 | 216 | 22 |
| BSh | 323 | 9 | 36 | | 14 | 40 | 161 | 72 |
| BSk | 151 | 4 | 36 | | 11 | 104 | 1 | 0 |
| BWh | 562 | 15 | 16 | | 8 | 131 | 314 | 93 |
| BWK | 146 | 4 | 3 | | 17 | 121 | 5 | 0 |
| Cfa | 159 | 4 | 57 | | 37 | 48 | 2 | 15 |
| Cfb | 75 | 2 | 5 | | 9 | 41 | 5 | 15 |
| Cfc | 15 | 1 | 8 | | 0 | 7 | 0 | 0 |
| Csa | 60 | 3 | 3 | | 0 | 42 | 10 | 5 |
| Csb | 51 | | 13 | | 3 | 29 | 1 | 5 |
| Cw | 172 | 4 | 0 | | 41 | 77 | 51 | 3 |
| Dfa | 51 | 6 | 35 | | 0 | 16 | 0 | 0 |
| Dfb | 180 | | 54 | | 0 | 126 | 0 | 0 |
| Dfc | 403 | 11 | 178 | | 0 | 225 | 0 | 0 |
| Dd | 85 | 2 | 0 | | 0 | 85 | 0 | 0 |
| Dwa | 10 | 1 | 0 | | 0 | 10 | 0 | 0 |
| Dwb | 30 | | 0 | | 0 | 30 | 0 | 0 |
| Dwc | 86 | 2 | 0 | | 0 | 86 | 0 | 0 |
| ET | 145 | 5 | 97 | | 3 | 45 | 0 | 0 |
| EF | 45 | | 0 | 45 | 0 | 0 | 0 | 0 |
| H | 284 | 7 | 57 | | 52 | 147 | 22 | 0 |
| Total | 3823 | 100 | | | | | | |

Note: Climate types are based on the Koppen-Geiger system of climate classification. First letter: A, tropical (all monthly mean temperatures over $64.4^{\circ}$F); B, dry (determined by formula based on mean annual temperature and precipitation); C, warm temperate (mean temperature of coldest month, $64.4^{\circ}$F; down to $26.6^{\circ}$F); D, Snow (warmest month mean over $50^{\circ}$F; coldest month mean under $26.6^{\circ}$F); E, ice (warmest month mean under $50^{\circ}$F). Second letter: S, steppe; W, desert; f, sufficient precipitation in all months; m, rainforest despite a dry season; s, dry season in summer; w, dry season in winter. Third letter: a, warmest month mean over $71.6^{\circ}$F; b, warmest month under $71.6^{\circ}$F; c, fewer than 4 months with means over $50^{\circ}$F; d, same as c, but coldest month mean under $-36.4^{\circ}$F; h, dry and hot; mean annual temperature over $64.4^{\circ}$F; k, dry and cold; mean annual temperature under $54.5^{\circ}$F; H, highland climates.

TABLE A-3. List of Stations and Data Used in Study.

| No. | | Data source* | Length of record, yr | Frequency of observations |
|---|---|---|---|---|
| 1 | Jacksonville, FL + Greensboro, NC | 1 | 10 | hourly |
| 2 | Springfield, IL | 1 | 10 | hourly |
| 3 | Baton Rouge, LA + Wichita Falls, TX | 1 | 10,5 | hourly |
| 4 | Burlington, VT + Green Bay, WI | 1 | 5 | hourly |
| 5 | Rapid City, SD | 1 | 5 | hourly |
| 6 | Portland, OR + Colorado Springs, CO | 1 | 10 | hourly |
| 7 | Phoenix, AZ | 1 | 10 | hourly |
| 8 | Boise, ID + Colorado Springs, CO | 1 | 10,5 | hourly |
| 9 | Fairbanks, AK | 1 | 5 | hourly |
| 10 | Anchorage + Cold Bay, AK | 1 | 5 | hourly |
| 11 | Paris, France + Aberdeen, Scotland | 2 | 10 | 3/day |
| 12 | Fargo, ND | 1 | 10 | hourly |
| 13 | Umiat, AK | 2 | 9 | hourly |
| 14 | Dawson Creek, Canada | 2 | 9 | hourly |
| 15 | Coppermine, Canada | 2 | 10 | 2-4/day |
| 16 | Resolute, Canada | 2 | 6 | 2-4/day |
| 17 | The Pas, Canada | 2 | 3 | hourly |
| 18 | Mingan, Canada | 2 | 8 | hourly |
| 19 | Frobisher Bay, Canada | 2 | 8 | hourly |
| 20 | Thule, Greenland | 2 | 4 | hourly |
| 21 | Tucson, AZ + Laredo, TX | 1 | 5,10 | hourly |
| 22 | Camaguey, Cuba | 3 | 4 | hourly |
| 23 | Guatemala City, Gautemala | 3 | 4 | hourly |
| 24 | Cristobal, Canal Zone | 4 | 10 | hourly |
| 25 | Barranquilla, Colombia | 5 | 10 | 5/day |
| 26 | Zanderij, Surinam | 5 | 6 | hourly |
| 27 | Iquitos, Peru | 5 | 10 | 3/day |
| 28 | Villavicencio, Colombia | 5 | 11 | 3/day |
| 29 | Talara, Peru + Pisco, Peru | 3,6 | 5,16 | hourly |
| 30 | Recife, Brazil | 3 | 3 | hourly |
| 31 | Falun, Sweden | 2 | 10 | 3/day |
| 32 | Budapest, Hungary + Warsaw, Poland | 2 | 9,11 | 3/day |
| 33 | Moscow + Ufa, USSR | 2 | 8,7 | 8/day |
| 34 | Kyev + Armavir, USSR | 2 | 8,6 | 8/day |
| 35 | Akmolinst + Dzharkent, USSR | 2 | 6,7 | 8/day |
| 36 | Chelkar + Ashkhabad, USSR | 2 | 7,8 | 8/day |
| 37 | Sevilla, Spain + Athens, Greece | 2 | 5,6 | 5-10, 3/day |
| 38 | Shenkursk, USSR | 2 | 6 | 8/day |
| 39 | Tientsin, China | 2 | 11 | 2/day |
| 40 | Asahikawa, Japan | 2 | 11 | 2/day |
| 41 | Kodinskoe, USSR | 2 | 6 | 8/day |
| 42 | Komsomolsk, USSR | 2 | 3 | 8/day |
| 43 | Mys Chelinskin, USSR | 2 | 6 | 8/day |
| 44 | Nyurba, USSR | 2 | 7 | 8/day |
| 45 | Tomsk, USSR | 2 | 8 | 8/day |

TABLE A-3. (Contd.)

| No. | | Data source* | Length of record, yr | Frequency of observations |
|---|---|---|---|---|
| 46 | Tulun, USSR | 2 | 6 | 8/day |
| 47 | Ust Kamchatsk, USSR | 2 | 7 | 8/day |
| 48 | Ust Port, USSR | 2 | 7 | 8/day |
| 49 | Zyrianka, USSR | 2 | 4 | 8/day |
| 50 | Kashgar, China | 2 | 1 | 3/day |
| 51 | Urga, Mongolia | 2 | 5 | 3/day |
| 52 | Lanchow, China | 2 | 8 | 3/day |
| 53 | Nanking, China | 2 | 10 | hourly |
| 54 | Kunming, China | 3 | 5 | hourly |
| 55 | Hanoi, Vietnam | 5 | 11 | 8/day |
| 56 | Kuching, Sarawak (Borneo) | 5 | 10 | 8/day |
| 57 | Chittagong, East Pakistan | 5 | 10 | 5/day |
| 58 | Urumchi, China | 2 | 2 | 3/day |
| 59 | Allahabad, India | 3 | 3 | hourly |
| 60 | Karachi + Jacobabad, W. Pakistan | 5,7 | 10 | 5,7/day |
| 61 | Bangalore, India | 3 | 3 | hourly |
| 62 | Meshed, Iran | 5 | 7 | 17/day |
| 63 | Dhahran, Saudi Arabia | 3 | 5 | hourly |
| 64 | Abadan, Iran | 3 | 2 | hourly |
| 65 | Tehran, Iran | 3 | 4 | hourly |
| 66 | Abu Hamed, Sudan | 5 | 6 | 8/day |
| 67 | Cairo, Egypt | 3 | 3 | hourly |
| 68 | El Fasher, Sudan | 3 | 2 | hourly |
| 69 | Wau, Sudan | 5 | 10 | 8/day |
| 70 | Coquilhatville, Congo | 5 | 5 | hourly |
| 71 | Tindouf, Algeria | 3 | 2 | hourly |
| 72 | Kamina-Baka, Congo | 5 | 5 | 7/day |
| 73 | Leopoldville, Congo | 5 | 3 | 8/day |
| 74 | Elizabethville, Congo | 5 | 5 | 8/day |
| 75 | Maiduguri, Nigeria | 3 | 2 | hourly |
| 76 | Atar, Mauritania + Dakar, Senegal | 3 | 2,1 | hourly |
| 77 | Madang, New Guinea | 5 | 7 | 6/day |
| 78 | Darwin, Australia | 5 | 8 | 14/day |
| 79 | Rockhampton + Sydney, Australia | 3 | 2,6 | 24,16/day |
| 80 | Gloncurry, Australia | 3 | 2 | hourly |
| 81 | Carnarvon, Australia | 3 | 4 | 8/day |
| 82 | Forrest, Australia | 3 | 4 | 8/day |
| 83 | Al Kufra, Libya | 7 | 7 | 8/day |
| 84 | El Golia, Algeria | 7 | 9 | 8/day |
| 85 | Aukland, New Zealand | 4 | 4 | hourly |
| 86 | Belem, Brazil | 4 | 5 | 8/day |
| 87 | Sheikh Othman, Aden (used twice) | 3 | 2 | hourly |
| 88 | Sheikh Othman, Aden (used twice) | 3 | 2 | hourly |
| 89 | Rivera, Uruguay | 6 | 6 | 3/day |
| 90 | Keetsmanshoup, S.W. Africa | 6 | 9 | 4/day |

TABLE A-3. (Contd.)

| No. | | Data source* | Length of record, yr | Frequency of observations |
|---|---|---|---|---|
| 91 | Francistown, Bechuanaland | 6 | 6 | 3/day |
| 92 | Chachapoyas, Peru | 6 | 9 | 3-4/day |
| 93 | Rio Gallegos + Neuquen, Argentina | 6 | 10 | 5/day |
| 94 | La Quiaca, Argentina | 6 | 11 | 4/day |
| 95 | Campo Grande, Brazil | 8 | 8 | max & min |
| 96 | Rio Branco, Brazil | 8 | 3 | max & min |
| 97 | Brasilia, Brazil | 8 | 3 | max & min |
| 98 | Niamey, Nigeria | 8 | 10 | max & min |
| 99 | Montepuez, Mozambique | 8 | 30 | max & min |
| 100 | Tibetan Plateau (area) | 9 | N/A | max & min |

*Data sources were as follows:

1. U. S. Department of Commerce, Weather Bureau. *Climatography of the United States No. 82; Decennial Census of United States Climate - Summary of Hourly Observations 1951-1960* (various cities and dates).

2. J. N. Raynor, ed. *Temperature and Wind Frequency Tables for Eurasia; ..... for North America & Greenland.* Arctic Meteorology Research Group Publications in Meteorology (various volumes). McGill University, Montreal, Quebec, Canada, 1960.

3. U. S. Army Natick Laboratories. *Bivariate Frequencies of Hourly Dry Bulb and Dew Point Temperatures for Low Latitude Stations* (various volumes), by A. V. Dodd. Natick, Mass., circa 1969.

4. Climatic Center, USAF, Fair Weather Service (MAC). *Revised Uniform Summary of Surface Weather Observations (RUSSWO). Part E. Psychrometric Summary* (various cities and dates), by Data Processing Division. Ashville, NC.

5. U. S. Department of Commerce, Environmental Science Services Administration, Environmental Data Service, National Weather Records Center. *Bivariate Distribution of Dry Bulb Temperature Versus Dew Point Temperature, by Day & Night, for All Months and Annual* (various cities and dates). Ashville, N. C., circa 1968. (Job No. 10062.)

6. USAF-ETAC, Air Weather Service. *Percentage Frequency Distribution of Wind Speed and Temperature, N Summary, Sect. 24* (various cities and dates), by Data Processing Division, Ashville, N.C.

7. Special computer tape runs received in 1978 from Dr. Essenwanter, U. S. Army Missile Command, Redstone Arsenal, Ala.

8. U. S. Naval Weather Service. *World-Wide Airfield Summaries* (various volumes and dates).

9. U. S. Army Natick Laboratories. *Environment of the Central Asian Highlands.* Natick, Mass., Earth Sciences Laboratory, December 1970. (Tech. Report 71-19-ES (ES-62).)

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